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MINUTES

ALUMINUM WELDING SYMPOSIUM

JULY 7, 8, 9, 1964

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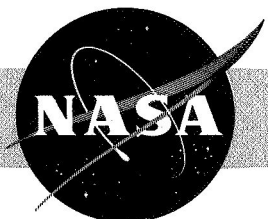
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National Aeronautics and Space Administration



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INTRODUCTORY REMARKS

By

Hermann K. Weidner

R-DIR  
RESEARCH AND DEVELOPMENT  
OPERATIONS  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
GEORGE C. MARSHALL SPACE FLIGHT CENTER  
HUNTSVILLE, ALABAMA

Aluminum Welding Symposium  
July 7, 1964

## INTRODUCTORY REMARKS

by

HERMANN K. WEIDNER

Gentlemen, it is a pleasure to welcome you to this Aluminum Welding Symposium. It is obviously a measure of your professional enthusiasm that you are willing to brave an Alabama summer and meet with us today.

Mr. Kuers has told me that there are representatives in the audience from about seventy-five companies and technical institutes. Many of you are in direct support of our Saturn programs. I notice from the roster of representatives that we have a good cross-section of the programs being conducted, today, throughout the national industrial plant.

None of you are strangers to the fact that present welding technology is now in a rapid state of flux. One of the main difficulties seems to be passing on the latest information to others in the profession. The out-pouring of knowledge is many times greater than available channels of dissemination. So, today, information exchange will be one major theme of our meeting. We hope to exchange experiences and share our common environment of professional problems. We, at Marshall, are bountifully provided with problems we can share with you.

At Marshall, we are responsible for NASA's large launch vehicle system requirements from conceptual design, through production and test, to flight evaluation.

In Mr. Kuers' Manufacturing Engineering Laboratory we have established a broad capability for research into manufacturing methods, and for development and experimental application of new manufacturing technology. Our emphasis is on the Saturn V, an extremely large vehicle. Its size, alone, has introduced a number of development problems. In addition, its performance requirements are most stringent. Operating environments are severe, and very high reliability and quality is required, because our vehicles will soon carry men.

These characteristics impose a number of interesting fabrication problems. We are faced by daily application of known techniques to advanced flight hardware. However, standard practices no longer meet all of our needs. The increased requirements of our vehicles forces us to extend our technology and this can only be done by going into basic, systematic technological development.

Solutions to our technical problems are not found by any single organization alone. Government must draw liberally on the broad experience of industry. We talk about the need for team work. We refer frequently to the government-industry team. One thing is clear--these demanding vehicles of ours depend on such pooled experience as we have represented here this morning.

At the beginning of this year, the Manufacturing Engineering Laboratory completed a survey of a number of companies to review current welding technology and the general problems being encountered by the aerospace industry. One conclusion stood out--Welding is still more than half art. During the course of the survey, a diversity of approaches and practices were identified, and a really surprising variety of equipment, philosophies, and programs were found.

The survey did find one thing common--we all had welding problems. These problems fall into certain basic groups. Equipment design, for example, and the effect of variations in base materials; the mechanism of porosity formation, and the need to investigate, in far greater depth of detail, the interrelationships of welding variables.

These problems are continuous. The old basic problems have an unfortunate tendency to remain with us. And, virtually everyday, we meet new ones in our shops at Marshall, or at our primes, or their supporting contractors.

However, it has grown increasingly apparent that welding technology is now at that point of maturity where it may prove most fruitful to pause a moment to formulate--as carefully and systematically as possible--our experiences and our philosophies. It is time we did so.

We have perhaps reached a point where art must be transformed to science. It is now possible to systematize our work and to begin formulation of the empirical and analytical tools needed in vehicle manufacture.

This, then, may be a second major theme of our symposium-- to stress science in welding. Our needs make that ambitious goal a most desirable one. We, at Marshall, have a vested interest in that enterprise. We have as our immediate objective, the improvement of welding techniques as applied to the Saturn V. We are yet a long way from having in hand all of the new developments and techniques required for that job.

Now, gentlemen, we have reached the end of the beginning. We are glad to have you here. We hope that the talks and discussions of this symposium will prove useful to you. And, incidentally, we hope that ways might be found for us to help you to help us.

Thank you.

TECHNICAL INTRODUCTION  
ALUMINUM WELDING SYMPOSIUM

By

James R. Williams

R-ME-M  
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HUNTSVILLE, ALABAMA

## TECHNICAL INTRODUCTION

### ALUMINUM WELDING SYMPOSIUM

"Before the end of this decade, man will launch his greatest voyage of discovery, a journey whose magnitude and implications for the human race dwarf any high adventure of the past. For the first time, he will leave his home planet and set foot upon another world, the luminous satellite of the earth we call the moon."

"More than 5,000 of the nation's industrial firms are directly involved in the United States' efforts to place men on the moon."

These are the words excerpted from a recent article titled "Footprints On The Moon", prepared by Dr. Hugh Dryden, who is the Deputy Administrator of NASA.

For ourselves, it is thrilling to be a needed part of such an exciting program. Each member of this audience truly has an important role in the potential success of the Apollo project. NASA is dependent on the collective experience and ingenuity of the welding profession across the nation to research new and better techniques of welding and importantly solve the day-to-day problems that plague our vehicle fabrication schedules.

We here at NASA are privileged to visit many research laboratories and production shops throughout the country and witness the best efforts of each organization.

Recently, Bob Hoppes, our symposium project officer, took part in a series of visits to many aerospace firms for the purpose of reviewing known welding problem areas and the work being performed by various organizations on particular problems. These findings are summarized in a Marshall Internal Note and copies of this report will be made available to symposium attendees at the close of the meeting on Thursday.

The cooperation extended by your companies provides Marshall personnel with a unique insight of problem areas and methods of possible solution being pursued by industry and research institutes.

The existence of many common aluminum welding problems has been a contributing factor in initiating the need and theme of this symposium.

The purpose of this symposium is to exchange technical data, to clarify common welding problems and to formulate direction for coordinating development effort. In theory and practice, if we know why a phenomenon occurs, normally we know how to make corrections when trouble develops. It is our hope that the papers selected for presentation in this symposium will provide more of the why which permits the subsequent control of the welding process.

The response from American firms to this symposium was gratifying. So many organizations offered to present papers that it imposed a real problem for the selection committee to choose those papers best suited to the interest of the symposium. A review of the agenda indicates that we have selected 17 technical papers for presentation whose subject matter includes the areas of statistics, basic metallurgical development, welding processes, and welding equipment.

We will have copies of the symposium technical papers available to the attendees on Thursday noon. Persons who may be required to leave before Thursday noon can obtain specific papers by writing to MSFC's Public Information Office.

You will also note on your program the scheduling of a panel discussion on Thursday morning, the last day of the symposium. One objective of this session is to stimulate our thoughts toward "defining tomorrow's problems in aluminum welding".

In a parallel activity to the theme of this symposium on aluminum welding, Marshall has recently awarded a number of research programs totaling approximately \$300,000. These investigations will include various studies such as basic material investigation, the mechanism of porosity formation, and the interrelationship of welding parameters.

Mr. Weidner has emphasized the need of transforming more of the art of welding into a science. In addition to many research programs which are directed to private firms, we at Marshall also contribute to development of basic knowledge. As one example, our welding engineers in the Manufacturing Engineering Laboratory are in the middle of an interesting scientific study which relates electrical energy input into the weld puddle to the specimens resultant quality and properties. This program was initiated as a result of the tough problem we are experiencing in producing good horizontal welds. As a result of this study, we have gained meaningful scientific guidance, and we are now approaching the problem of horizontal welding with more confidence and anticipated success. One of our metallurgists will present a paper tomorrow on this subject, titled "Time-Temperature Effect On Welds In 2219-T87 Aluminum Alloy". I'm sure you will find it very interesting and worthwhile, and the information might help solve one of your immediate problems.



Good fortune has been riding with much of our space program to date, and the group of professional welding engineers in this auditorium has a special responsibility to keep the chain of success continuous. The Mercury program was initially daring and later became glamorous. The current Saturn I Launch Program has provided the brute power to pave the way for man's footprints on the moon. The 360' tall Saturn V vehicle that so many of you are personally acquainted with will bring manned lunar exploration into reality.

The shops here at Marshall, at Boeing, at NAA and Douglas are now fabricating the prototype stages of Saturn V vehicles. When assembled vertically, the vehicle will stretch skyward but a fraction of the quarter million mile distance to the moon. The remaining distance to success will be a reality only if you and your associates share this task.

We have arranged a tour for you immediately after lunch today through two areas: First, to the static test stand area, and then through the Manufacturing Engineering Laboratory's shops.

The test area is where all vehicles are statically test fired prior to the journey to Cape Kennedy. If you look southward, about one mile from the front of this Building, you will note a very large structure raising its head above the horizon. This is the static test stand designed for retaining 7 1/2 million pounds of thrust which will be generated by the Saturn V vehicle. The rumble heard from the test stand area is a frequent occurrence as the test firing program progresses.

The Manufacturing Engineering Shop tour will give you an opportunity to see the huge first stage components being constructed of the Saturn V launch vehicle. We have in various stages of completion all the major components of the S-IC stage of the Saturn V vehicle. Of special interest to most of you will be the all-welded LOX and fuel tanks, both 33' in diameter and representing horizontal, vertical, and conventional flat welding, all automatic.

Also of special interest to any of you who lived in the "Rivet Together Era" is the monstrous thrust structure. This item really looks as if it should be shipped to a bridge construction project.

We are finalizing the development of electron beam welding for the 33' diameter Y-ring of the S-IC Saturn. During your shop tour this afternoon, we will have our operators at the station to explain the welding demonstrations of the equipment and show results of the work accomplished to date. The results of the development are impressive. We at Marshall believe the electron beam process has a unique place in the future for welding heavy gage aluminum structures.

The challenge of space exploration is a very real thing, and like Mount Everest, it will be conquered because men try and it is possible. The goals of the space program can only become reality through your collective technological intelligence and efforts. I'm sure each of you is proud and thrilled to be associated with this history-making program.

THANK YOU

INFLUENCE OF WELDING PARAMETERS IN  
ELECTRON BEAM WELDING ALUMINUM ALLOYS

By

Walter Schwenk

MANUFACTURING ENGINEERING  
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BETHPAGE, NEW YORK

## ABSTRACT

This report summarized the work performed in evaluating the influence of the welding parameters in electron beam welding aluminum alloys. The program was divided into two phases: Phase I was an investigation to determine the effect on weld bead geometry caused by varying the parameters; Phase II was a study concerned with deriving a relationship between the welding parameters and 100 percent penetration.

The following parameters: focusing current, carriage speed, gun-to-work distance, beam current, and accelerating voltage were optimized for the material being investigated. Then the effect of varying these parameter from the optimum setting on the penetration and geometry of the weldment was studied. To accomplish this, one parameter at a time was varied from the optimum setting while all of the others were held constant. All of the welding tests were performed using the minimum beam diameter for a given power level. This minimum beam diameter was accurately determined by a technique developed in our laboratory. The results of the tests showed that the power density of the electron beam was the most important parameter in controlling weld penetration while variations in carriage speed produced only a slight effect on penetration.

A relationship was derived between welding parameters and penetration. The energy input required to produce 100 percent penetration was calculated from all the data generated in our studies pertaining to electron beam welding aluminum alloys. A graph was obtained by plotting material thickness vs. energy input required to produce a weld possessing 100 percent penetration for any given thickness. It is then possible by the use of an equation, to convert energy input to actual welding parameters.

## CONCLUSIONS AND RECOMMENDATIONS

The results of this program show that the power density of the electron beam is the most important welding parameter. This power density is determined by three variables, i.e., accelerating voltage, beam current, and beam diameter. Carriage speed is shown to have a slight effect on weld penetration and weld bead geometry.

A relationship was obtained between welding parameters and penetration. It is possible to obtain from a graph the energy input required for 100 percent penetration of any aluminum alloy thickness; then the energy input can be easily converted into actual welding parameters.

Future welding studies should include a study of the interrelationship between welding parameters and mechanical properties. This would enable an operator to obtain from a graph the parameter settings required to produce a weldment possessing both maximum mechanical properties and satisfactory quality. This work should also be extended for other materials, especially ferrous alloys.

## INTRODUCTION

Electron beam welding (E.B.W.) was introduced to the welding industry approximately seven years ago. At that time it was thought to be the panacea for all welding problems. However, at present the majority of the units are

still being utilized in research and development laboratories. This is probably a result of numerous unanswered questions posed by the process; these questions must be answered before E.B.W. will become accepted in all welding industries.

This program was initiated as an attempt to solve some of the basic problems associated with E.B.W. Phase I was an investigation to determine the effect on weld bead geometry caused by varying the welding parameters. Welding parameters investigated were accelerating voltage, beam current, focusing current, gun-to-work distance, and work table movement. Phase II was a study designed to derive a relationship between the welding parameters and 100 percent penetration in the thickness of material to be welded.

## PROCEDURE

### Phase I

The material used in this phase of the program was 0.500 inch thick aluminum alloy 7075-T6. All of the welding was performed using a low-voltage, high-power electron beam welder.

The following parameters were optimized for the material by visual and microscopic examination of test weldments: focusing current, carriage speed, gun-to-work distance, beam current, and accelerating voltage. Then a study was made of the effects of parameter variations, particularly as they applied to weld penetration and weld geometry. To accomplish this, one parameter at a time was varied from the optimum setting while all the others were held constant (at the optimum settings). In the last test, however, the beam current was maintained constant at 100 milliamps and the focusing current had to be varied in order to maintain a beam.

Test I - Focusing Current - (Optimum value was 7.5 amps)  
Six passes were made using various focusing currents from 6 to 8.5 amps.

Test II - Carriage Speed - (Optimum value was 45 IPM)  
Variations from 30 IPM to 75 IPM were made on the carriage speed.

Test III - Gun-to-Work Distance - (Optimum value was 1 inch)  
Distance between the electron gun and the work was varied from 3/4 inch to 2 inches.

Test IV - Beam Current - (Optimum value was 155 Ma)  
The variations in beam currents were 115, 130, 110, 90, 65, and 30 Ma.

Test V - Accelerating Voltage  
The voltage was varied from 25.5 KV to 15 KV

### Phase II

Data from the electron beam welding of aluminum alloys at Grumman Aircraft Engineering Corporation were obtained and tabulated. This data,

however, pertained only to thicknesses between 0.020 inch and 0.625 inch. Parameters listed were accelerating voltage, beam current, and carriage speed in addition to material thickness. Various attempts were made to derive a relationship between the welding parameters and penetration.

## RESULTS AND DISCUSSION

### Phase I

The optimum welding parameters were obtained for 0.500 inch thick 7075 aluminum and are as follows:

Voltage	25,800 Volts
Beam Current	155 Milliamps
Carriage Speed	45 Inches/Minute
Focusing Current	7.5 Amps
Gun-to-Work Distance	1 Inch

The weld bead exhibited the typical shape of an electron beam weld in that it possessed a depth-to-width ratio of approximately 16:1. (See Figure 1.) The weld was not tested either mechanically or radiographically as neither was pertinent to the program. It is recommended that weld beads of this configuration be approached when welding various alloys and thicknesses. A narrow weld zone is desirable as it usually increases the strength of the material. A weld, as shown in Figure 1, will also decrease the amount of distortion caused by shrinkage.

The results of the tests, showing the effect on the weld bead caused by varying the welding parameter, were satisfactory and a considerable amount of information was obtained. Some of the tests substantiated previous assumptions of the process; others showed us the effects of the parameters on the weld bead.

Observations of the test showed the following:

#### Test I

Prior to the test, the focusing current was known to have a considerable effect on the weld bead shape. The test proved this statement was valid since a defocused beam produced a wide weld zone with insufficient penetration. The larger beam diameter decreased the power density of the beam, which is undesirable. The power density of the beam was shown to be the most important factor in obtaining a narrow weld zone. This is shown in Figure 2.

#### Test II

The carriage speed was thought to have a large effect on penetration and shape of the bead. However, the test showed that the carriage speed had very little effect on the shape of the bead and penetration. The first three passes showed that there is only slight change in penetration when the carriage speed is decreased by 33 1/3 percent. (See Figure 3.) This discrepancy is attributed to the forementioned fact that the electron beam density is the most important variable in obtaining a narrow weld.

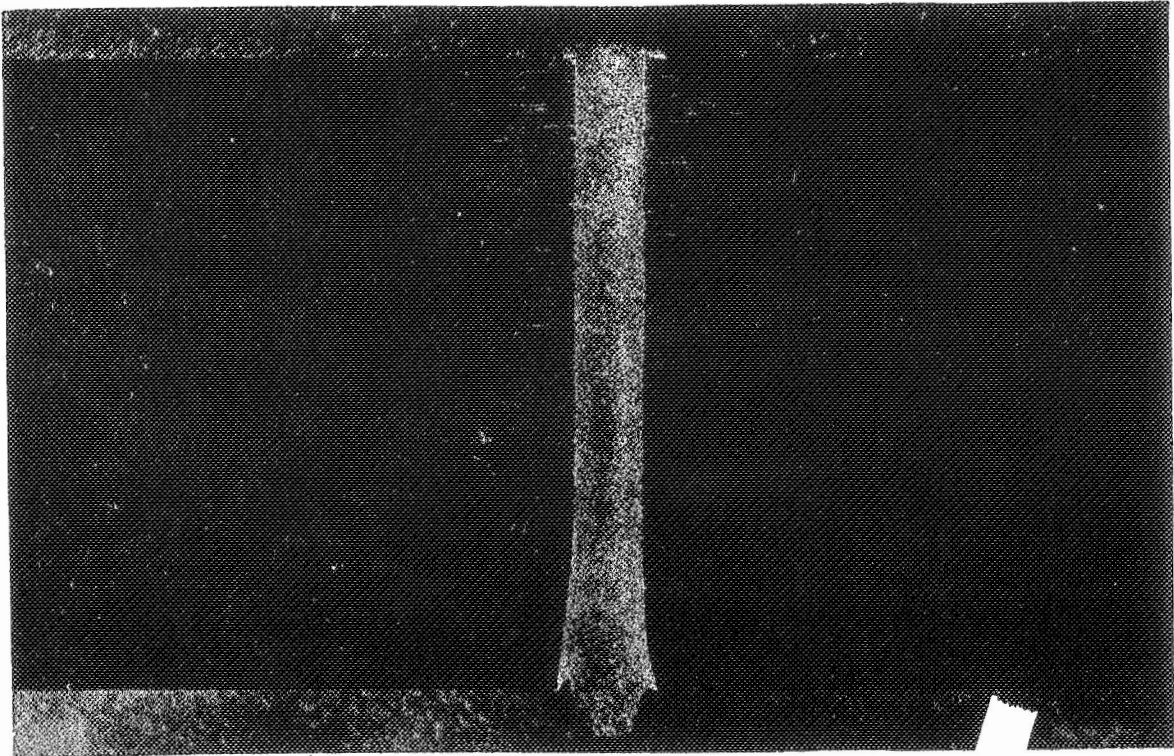


Figure 1. Butt Weld  $\frac{1}{2}$ -Inch Aluminum

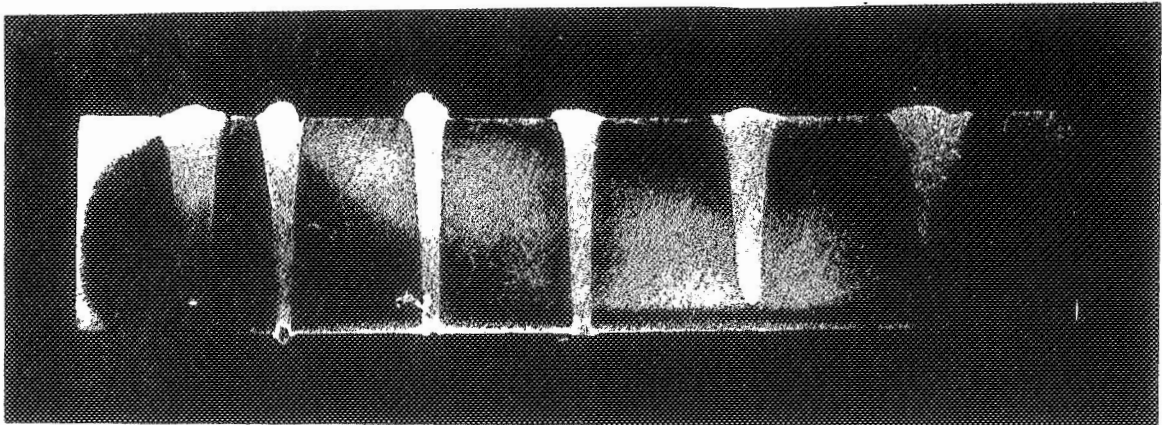


Figure 2. Effect of Varying the Focusing Current. Focusing Currents from Left to Right are 6.0, 6.5, 7.0, 8.0 and 8.5 Amp

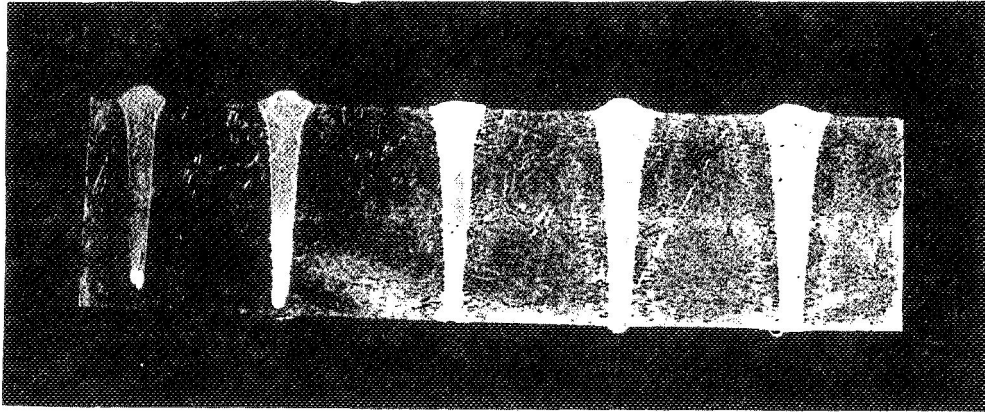


Figure 3. Variations in Weld Bead Caused by Changing Carriage Speed.  
Carriage Speeds from Left to Right are 75, 60, 50, 40, and 30 IPM

### Test III

The distance between the gun and the work piece is a critical parameter. Prior to the test this parameter was thought to have only a slight effect on the weld bead. The test, however, disproved this hypothesis: welds with various shapes were produced by varying the distance. (See Figure 4.) Actually, when this distance is varied, the cross-sectional area of the focused beam at the work surface changes and causes the various weld bead shapes.

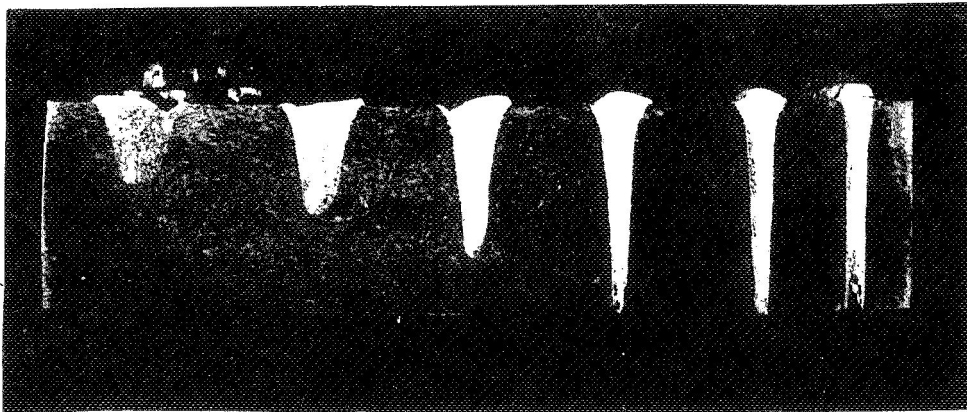


Figure 4. Effect of Varying Gun-to-Work Distance. Distances from Left to Right are 2, 1 3/4, 1 1/2, 1 1/4, 1, and 3/4 Inches.

#### Test IV

It was known prior to the test that the beam current had considerable effect on the amount of penetration and the shape of the weld bead. (See Figure 5.) The test, however, showed that variations in the beam current had considerable effect on the penetration and only a slight effect on the shape of the bead. The decreasing variation in beam current caused the energy density of the beam to decrease, thus causing a loss in penetration.

#### Test V

Variations in accelerating voltage had a considerable effect on the weld bead geometry. (See Figure 6.) In this test the only variables were the voltage and focusing current. The beam current was not 155 milliamps, as it was in the other tests, however, it was maintained constant at 100 milliamps.

Tests showed that slight variations in four of the variables will produce a noticeable change in the weld bead geometry. These four variables (voltage, beam current, focusing current, and gun-to-work distance) determine the power density of the beam; the latter two variables determine the diameter of the beam. Variations in the focusing current and gun-to-work distance vary the beam diameter at its intersection with the work piece. Both parameters will vary the location of minimum beam diameter in relation to distance from the work piece.

The majority of the welding, using this unit, is performed with a gun-to-work distance of 1 inch. The minimum beam diameter at the intersection with the work pieces is then obtained for a given power level by varying the focusing current until the desired beam diameter is reached. The minimum diameter was determined previously by a technique developed in our laboratory that utilizes a tungsten rod passing through the beam at a known velocity. The time required is recorded and related to beam diameter.

#### Phase II

This phase was primarily a compilation of all the data generated from welding studies on our unit pertaining to electron beam welding aluminum alloys. Welding data from numerous aluminum alloys were used as variations in composition showed only a slight effect on the interrelationship obtained.

The welding parameters which form the interrelationship are listed in Table I. Energy input is easily obtained by using the following equation:

#### Equation (1)

$$\text{Energy Input} = \frac{\text{Voltage (volts)} \times \text{Beam Current (amps)} \times 60}{\text{Carriage Speed (In./Min)}} = \text{Joules/in}$$

All of this welding was performed with the minimum beam diameter at the work piece surface. Therefore, the maximum energy density/energy input was used and should be used in all subsequent welding operations.



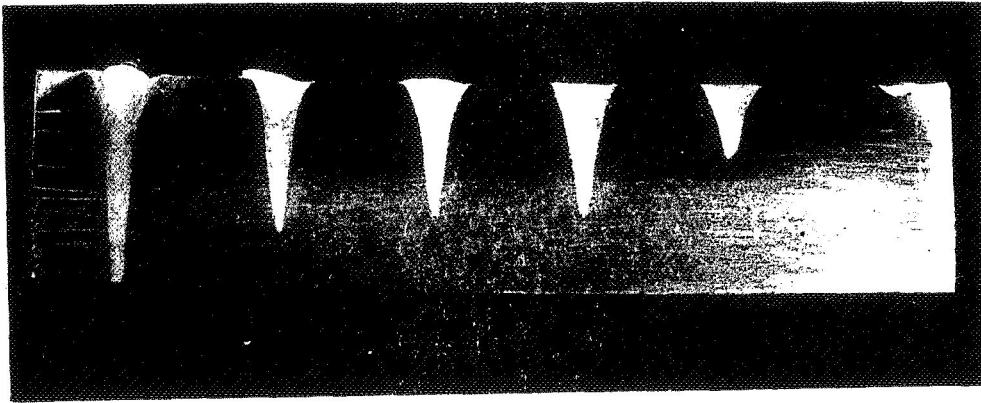


Figure 5. Effect of Varying the Beam Current. Beam Currents from Left to Right are 155, 130, 110, 90, 65, and 30 Milliamps

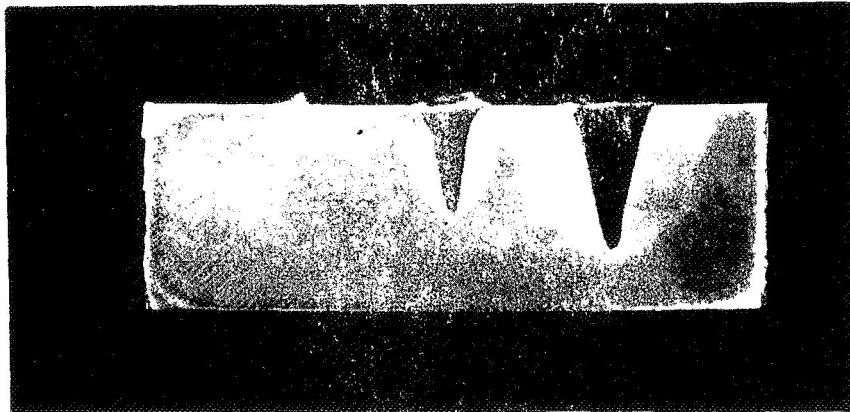


Figure 6. Variations in Weld Bead Geometry Caused by Changing Accelerating Voltages. Voltages from Left to Right are 15, 20, and 25.5 KV.

Table I. Aluminum Alloys,

<u>Alloy</u>	<u>Thickness In.</u>	<u>Accelerating Voltage (KV)</u>	<u>Beam Current (MA)</u>	<u>Speed In/Min.</u>	<u>Energy Input Joules/In.</u>
7075-T6	0.020	8.5	25	95	132
6061-T6	0.050	18	38	100	408
3003-0	0.063	17.5	44	60	780
2219-T31	0.064	17.5	56	75	780
2219-T31	0.100	21	76	75	1260
2020	0.100	17.5	72	60	1260
2219-T87	0.100	24	67	85	1140
7075-T6	0.125	20	75	70	1260
7075-T6	0.125	25	80	90	1332
7075-T6	0.125	25.2	62	75	1260
5052	0.250	20.5	140	66	2640
2014	0.250	23.4	92	50	2580
7075-T6	0.500	25.8	155	45	5440
2014	0.500	30	235	67	6300
6061	0.625	30	250	65	6900

A graph was obtained by plotting material thickness vs. energy input. (See Figure 7.) Using this graph an operator can obtain the energy input required to produce a weld possessing 100 percent penetration for a given thickness of aluminum. Then using equation (1) (and using arbitrary values for two of the unknowns) it is possible to obtain the proper welding parameters.

Obviously there are some limitations in the use of this method for obtaining the proper welding parameter settings. The electron optics of the electron gun usually determine the beam current for a given accelerating voltage. But by the use of spacer rings or variations in grid potential a great many combinations of current and voltage settings may be obtained. Therefore, with the above two known settings the third variable, carriage speed, can be obtained easily. Carriage speed is usually the last parameter to determine as it has the least effect on the penetration. Previous tests have shown that for a given energy input, parameter settings can be varied up to 30 percent and have no effect on the penetration of the weld. They will, however, have a noticeable effect on the shape of the weld bead. In some instances, the weld bead looks very similar to one produced by the gas tungsten arc welding process.

It must be stressed again that this data and graph were obtained on only one type of machine, so the values might be incorrect for a different machine. This could be caused by difference in gun optics and variations in minimum beam diameter. However, this author anticipates that the same theory will apply to each type of machine and that the same results will be exhibited only at different values.

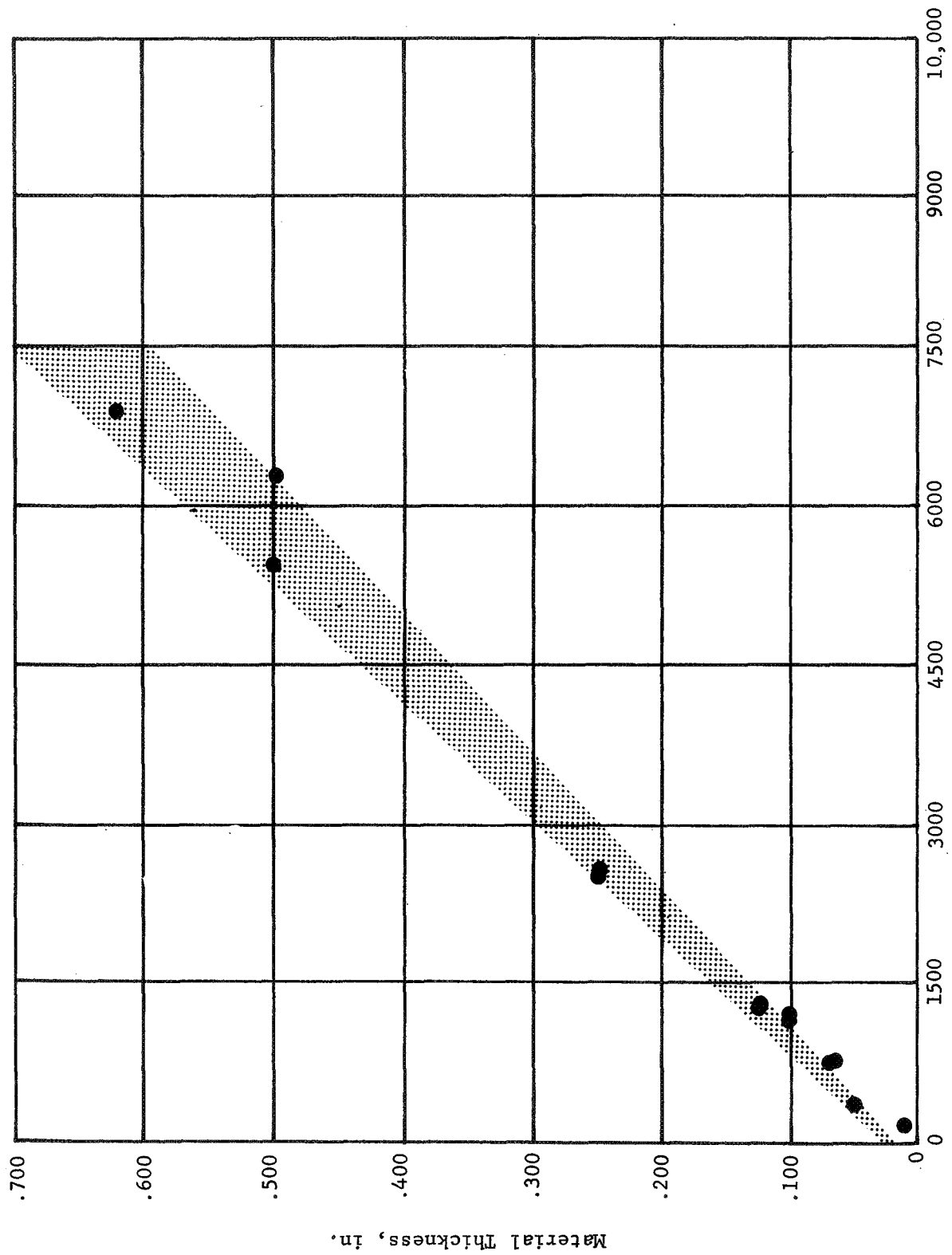


Figure. 7

## DISCUSSION

Question: Not audible

Mr. Schwenk: Yes, I would say that in our studies of electron beam welding 2020 aluminum, we found that there was a tendency in all our welds to vaporize the lithium quite easily, thereby producing porosity in weldments. They were approximately equal to the TIG weldments. We found there was no advantage in electron beam welding 2020 aluminum over conventional TIG welding.

Question: You pointed out in the very beginning, a relationship between the focal current and the penetrations. I would like to inquire where the focal point was physically in the part. This we found at Hamilton in our high voltage equipment to be more meaningful than specifically just the focal current. Furthermore, at another point you indicated that you varied the location of the sample with regard to the focus coil. You did not change the focal current; however, this will also change the focal point with regard to where it is in the part. Would you care to comment on that?

Mr. Schwenk: I will take your second question first, and then I will go to your first question. Yes, this is a known fact that if you vary the distance between the focal coil and the workpiece you will vary the location of the focal point or the location of the minimum beam diameter. We knew this before we performed this test. It was more of an academic test. We did not want to produce all optimum weld beads and have them all identical, we just wanted to find out what effects this would produce by varying the distance between the coil and the workpiece. In regard to the first question, we desired to have the minimum beam diameter. In most of our studies, we have found either the top of the workpiece surface or down half-way between the workpiece surface and the body, half-way through the material, to be the best location for the minimum beam diameter or the focal point, whichever you care to call it.

Dr. Savage; Drawing on the experience of other welding processes in using the energy input as a parameter describing penetration, or what have you, something is missing. It seems to me that if you use a differing depth-to-width ratio for different thicknesses, the volume of the heat-affected zone changes because of differences in the heat transfer characteristics. Therefore, it seems to me that you must define some other parameter before you can draw that nice curve you have there.

Mr. Schwenk: The only answer I have to that, is maybe in our studies as you saw on the optimum weld bead, we did have somewhat excessive penetration. I think this might overcome that problem. We are well aware that the wider you get in the weld zone, the more heat transfer you get in the basic material, thereby, increasing the heat-affected zone and decreasing the penetration; however, we have found that we could go right to the graph and still obtain 100 percent penetration even with a short stubby weld. This could be caused by the thickness of the material. We did not go into real thick material. It is our assumption that this might work okay on thinner gage material; however, I do agree with you that this would be a very important factor in going into much thicker material above what we worked on.

Mr. Chyle: One of the problems we have is the undercuts we get on the top side. I noticed on your slides that you did have undercuts. Isn't it true that this is a problem -- getting these shallow undercuts along the edges? How do you get rid of those?

Mr. Schwenk: Believe me, if I knew, I would answer all the questions, because right now I have two projects, one on titanium and one on ladish D6AC where the requirements are that they possess no undercuts. Actually, I don't know how I am going to get around that because they will not accept beautifying passes. Industry is not that worried about the properties of the weldment, and it is not that critical to go over the first pass with a sort of a defocused beam, or a beam of less power to put a cosmetic or beautifying pass to remove the undercuts. However, on my work, I cannot do that, and we are running into one heck of a problem trying to remove the undercuts. I have to admit that on those other samples there were undercuts. Maybe it did not show up on the exact cross section I showed on the slide -- I did not mean it that way -- but we still get undercuts on most of our welds. I will say one thing, on a thinner gage there is a tendency to get away from the undercut. I did do a weld on titanium, where we had the requirement "no undercut". In order to overcome this, I decreased the speed and everything down to almost nothing. I got a resultant TIG weld using the electron beam process, and this weld did not have an undercut.

Mr. Orr: I like that "beautifying pass". I think I'm going to remember that one.

Question: Don't you feel that the information you got, even though it is extremely useful, is very specific to the gun design that you used? The question comes to my mind what type of gun it is -- is it a diode, triode? I know it is low voltage.

Mr. Schwenk: This was a Pierce-type gun.

Question: It is my feeling that when you present information such as this you should be very specific about the gun design, which I feel is a very important parameter.

Mr. Schwenk: I go along with that 100 percent. I think I stated that all of this data pertained just to our machine, although I feel the same theory behind what we performed and the energy input will be applicable to other types of machines. This is getting now into a metallurgical and heat transfer problem which is not dependent on the type of heat source.

Question: The question I have in my mind is whether the same kind of trend would be obtained with a high or low voltage. I am not sure it would. I think your optimum condition might be spread out to a much greater degree than you have here.

Mr. Schwenk: Then you have a different minimum beam diameter. Am I correct in assuming that the minimum beam diameter is much larger with that type of gun than it is with ours, or the gun we used in our study?

Mr. Lenamond: I am curious about the filler metal in the electron beam. What work is being done with the filler metal? Also, what is being done about taking the beam out of the vacuum?

Mr. Schwenk: I think there is a gentleman in the audience who could answer the question about taking it out of the vacuum better than I could; however, I will try to answer that question. Hamilton Standard has been spending quite a bit of money and time in developing a welder to weld outside of a vacuum. Alloyd General in Boston, Mass. had a contract with the Air Force about two years ago, and when that contract expired, Hamilton Standard then was awarded an AF contract. From what I can understand, they can weld about 3/4 inch stainless steel outside of a vacuum on their unit. As far as the use of filler metal, I think in the AIA specification, which was just accepted, there is a provision that the manufacturers have to supply a wire feed unit within the chamber for filler wire addition while welding.

Question: Did that tend to alleviate the undercut you have?

Mr. Schwenk: Yes, this is the assumption of a number of people in the industry, that if you add filler wire you should remove the undercut; however, we have not employed any test in the use of filler wire. I did one very simple experiment on molybdenum where I found the addition of filler wire did not solve the undercut. I do not feel this is synonymous throughout all welding schedules.

Mr. Orr: I think we would all like to weld out of a vacuum. Gordon Parks, do you have anything you would like to say about a couple of programs we have on Plasma Electron Beam that we have some hopes for?

Mr. Parks: A recently established contract between the General Electric Advanced Technology Laboratories and NASA, Marshall Space Flight Center, will develop the plasma electron beam welding process for application to space vehicle fabrication. The PEB process offers the potential of welding in a low pressure, inert gas atmosphere, helium or argon, thus reducing the mechanical problems of the hard vacuum system. Pressures of 1 to 50 microns are used with this process. With the application development of this process, it will be possible to use small portable chambers similar to bell jars. Continued development should permit the out-of-chamber application.

Mr. Orr: Thanks, Gordon.

Mr. Wuenschel: Did you look into the dependency of the energy input requirement of penetration on the different alloys? In other words, did you assort your high strength aluminum alloys with respect to the energy requirement to find out whether the copper content or the magnesium content in this certain alloy would promote the penetration or minimize the energy requirement?

Mr. Schwenk: No, I would say we did not look into it that closely; however, all the data I have listed here did pertain to the 6 and 7 thousand and 2 thousand series alloys. However, we did have some 3 S aluminum and we tried other aluminum alloys. We found that within a small range -- you notice that was not a straight line, it was more of an area -- we could get 100 percent penetration in all the aluminum alloys which we investigated. So, I would have to say right now that to my knowledge, the actual content did not have that much of an effect on penetration or the weld bead configuration.

Mr. Wuenschel: On the other hand, it showed that when you go to a thicker gage, your diagram went up to half an inch or an inch. If you go to a 4 or 5 inch gage, then your band width is very wide. You might have a great difference in energy requirement depending on the alloy.

Mr. Schwenk: Yes, I agree with you one hundred percent, and the only thing I can add is that I think that maybe on some of the newer machines -- our machine is approximately 3½ years old--which have the capability of welding 5 and 6 inches of aluminum, that the band would not be as wide as you approach 7/10 inch thickness. This is approaching the maximum thickness that is weldable on our machine, and I think that is why we are getting a scatter. The graph was not that good; the limits were too far apart. The presentation people drew up the draft, and I think they could have made the limits much closer.

Mr. Wuenschel: Yes, that is the question, whether that band width comes from the different alloys, for you had a large number of different alloys, not just one, or whether this is the inaccuracy of the test.

Mr. Schwenk: I would say there is primarily some difference in the penetration due to the composition of the aluminum alloy; however, we found in our work that this only had a very slight effect on the graph.

Mr. Martin: How much vacuum did you have under those tests you recorded? What was the strength of the weldment to the unwelded specimen, that is, the specimens which you required to have an acceptable weld? What standards do you have on the weldments?

Mr. Schwenk: The first question is very easy to answer. We welded under a pressure of  $1 \times 10$  to the minus microns, or milometers of mercury for 1/10 of a micron of pressure. To the second question, I would say that in most of our studies, we did not evaluate or destructively test the weldments that were produced. We looked at them more from a metallurgical standpoint instead of from a mechanical standpoint. Some of these alloys, like 7075-T6 aluminum, we did test destructively, and we got results slightly superior to those exhibited by TIG welding; however, there was no major difference. In 2219, we did find a very slight increase of properties over those produced by conventional welding. These were about the only ones we tested mechanically.

Question: What was the approximate ratio of strength in unwelded to welded specimens?

Mr. Schwenk: I would say that on the 7075, it was around 75 percent and on the 2219, it was around 42,000 psi on the -T87 condition.

Mr. Robelletto: I would like to comment on one thing. We have just completed a program for NASA on EB welding, and our results more or less confirm those of Mr. Schwenk on the effect of material on penetration. We did not find very much difference between copper-bearing and magnesium-bearing alloys. However, there was quite a substantial difference in the width of the weld. Another thing we determined was that beam oscillation was very effective in changing the depth of penetration even with constant energy inputs.



Mr. Schwenk: That is one way of removing some of the undercuts. You might possibly be able to remove the undercuts by deflecting the beam transverse to the weld bead. This, in some cases will remove the undercut. Normally, it would be parallel to the weld bead. On some units you can oscillate the beam transverse to the weld bead, and this will remove some of the undercuts.

Mr. Gaw: I would like to inquire a little more about your technique for measuring the diameter of your electron beam. We have talked about the importance of determining these variables pretty specifically, and in order to make this conference realistic, I would like to establish the means by which you fix your beam diameter prior to making the weld?

Mr. Schwenk: This again is by the use of graphs, and as the gentleman usually says when he gets up to make an impromptu speech, "Well, I just had the speech in my pocket." I just do have slides to show this. I felt that this would be a question, and I think by use of slides I can show it much easier than if I went up there and tried to explain it in my own words.

Mr. Orr: You have slides right now?

Mr. Schwenk: Yes, prior to putting on the slide, I will try to tell you what we did. We rotated a tungsten rod 1/16th inch in diameter through the electron beam. This rod was rotated through the beam at an average speed of 1100 RPM. Then, we picked up the electrical input from this rod, and we fed it to an oscillograph. We then took polaroid pictures. We could get a little blip like this on the pictures, and by relating the speed of the rods, we then determined what the minimum beam diameter was. This is basically a very simple oscillograph with a polaroid camera right here. Now, all of these wires coming in go through the chamber. Of course, during our study, the doors are closed, and we operate in a vacuum. This is the tungsten rod right here; we pass this through the beam. The beam is directed on a copper block. The copper block is this finger, and the rod will pass like so through the beam which is hitting the copper block. We then pick up the electrical input on this rod. We feed it to the oscilloscope, and by this means, we can then determine the minimum beam diameter for a given voltage level.

Question: How is that sensitive to the focus? For impact?

Mr. Schwenk: Yes, this is dependent both on focus and beam diameter. From this procedure, we determine the distance or the focusing current we have to apply in order to obtain the minimum beam diameter. I think maybe the next slide will show it clearer. Well, this is essentially it. This is a little flywheel. Coming out right here is the tungsten rod which will intercept the beam. And by picking up the electrical input on the oscillograph, and taking pictures of it, we are able to determine the width of the beam. We took a given voltage, say 15 KV, with the maximum beam current obtainable for that voltage. We kept a one inch distance between the rod and the electronic gun, and we varied the focusing current. This then showed us different time elements on the scope, thus we could determine the minimum beam diameter for a given voltage.

NEW CONCEPTS FOR THE DESIGN, CONTROL,  
AND EVALUATION OF TEST WELDING

By

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When we tell engineers and scientists how to design experiments we run the risk of insulting someone or at least we risk boring everyone with the fundamentals of cause and effect and logic. However, after living with these problems in our own shops and labs throughout the industry, it became apparent that a better method of weld experimentation and evaluation was badly needed.

How often do we read welding reports that contain conclusions that are just not supported by the data? How often do we attempt to test the effect of some particular weld variable without having the process under control or perhaps without taking the time to determine in advance what technique of evaluation will be used? How often have we seen conclusions drawn from tensile data that one treatment is superior to another when there is more variation between tensile values within each treatment than the variation between the average values used to compare treatments? In this example there is no significant difference between treatments. To the statistician this statement is no vague generality or matter of opinion, rather it is a precise statement arrived at through very exacting mathematical calculations.

Several years ago we made a quiet survey of the leaders in aircraft welding and found that everyone was using the "cut and try" system of weld optimizations. This system of course was only as good as the experience and skill of the engineer. However, the criterion for success was the ease with which a weld was produced rather than specific physical properties.

With the advancement of instrumentation suitable for recording the basic welding variables or parameters, we come to the "classical" scientific technique of analyzing the effect of each variable by changing only one of them at a time while holding the others such as voltage, current, travel speed, or wire feed constant and observing responses or the change produced in the weld.

The data obtained from this experimental design is easy to analyze but severely limited as to the inferences that can be made from the resulting data.

For example, if we plot the three welding variables of current, voltage, and weld travel on an  $X_1 - X_2 - X_3$  axis to form a cube we can visualize the points at which data is taken for a "classical" experiment. With an assumed optimum weld setting represented by the center of the cube we explore in all three directions along the axes leaving most of the cube completely unexplored. No repeat runs or replicates are made; therefore, the confidence limits of the results cannot be calculated. Also, very little can be inferred about possible interactions between the variables in combination. (See Figure 1.)

Now lets try a statistically designed experiment. A statistically designed experiment is a plan for taking data so that the least data points give the most data and the most reliable information. The plan must include the system of analysis to be used.

We can compare a very simple "rotatable" design to the "classical" design previously illustrated.

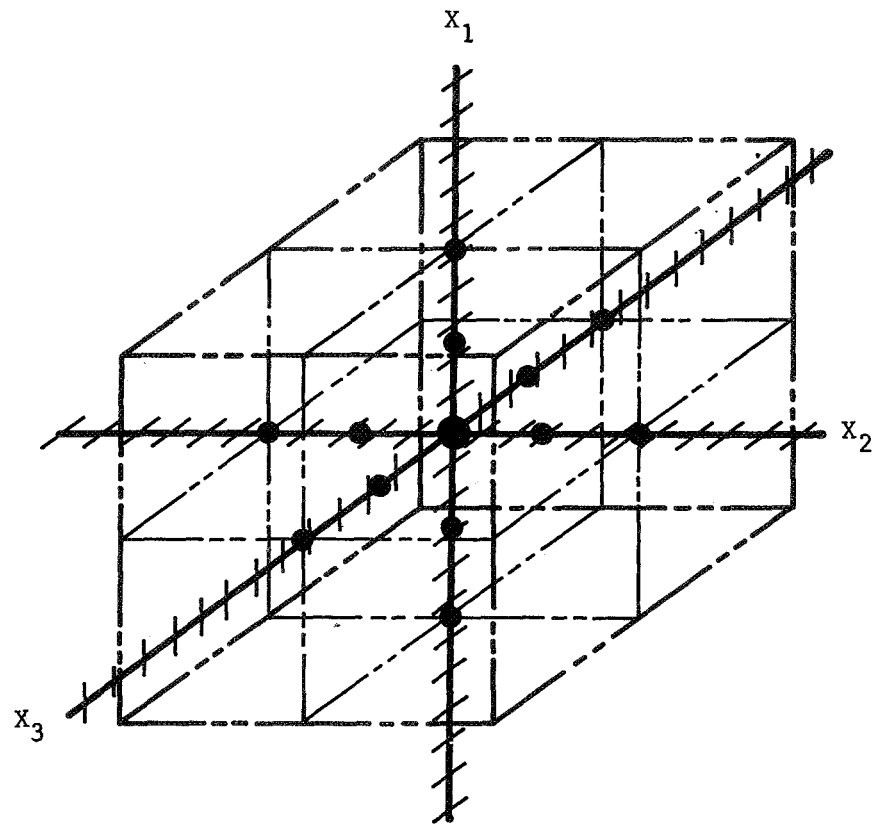


Figure 1. Data Points for Classical Experiment Design with Three Variables.

In the case of the statistical, rotatable, design for analyzing the effect of the variables, we can visualize the same cube with the assumed optimum setting of the three variables at the center. The statistical design may call for a data point at each corner of the cube and one at the same distance beyond each cube face center and perhaps 5 replicates clustered around the assumed optimum. From the illustration it is apparent that the entire volume of the cube is explored. From an analysis of the results very accurate inferences may be made as to any interactions between the variables. Since the rotatable design provides an estimate of experimental error, we are also able to compute 95 percent and 99 percent confidence intervals about the responses. One advantage of this design is that this confidence interval is approximately uniform over the range tested. (See Figure 2.)

We are unable to visualize more than three dimensions; however, the computer has no difficulty handling simultaneously as many as 10 variables and as many responses.

The statistical branch of mathematics is not new. However, its application was limited due to the tedious calculations involved. In order to reduce the manhours involved in calculations, the solutions were often over-simplified, thereby reducing their effectiveness. The high speed, digital, computers changed that. Problems previously requiring years on a desk calculator now require only minutes on the computers.

Today the engineer and statistician together form a very powerful team. The welding development engineer who does not avail himself of the services of the statistician and computer will be operating at a severe disadvantage.

In this profession we enjoy coining and adopting colorful words and phrases to describe our processes. Remember how the words configuration and parameters caught on? Now we have a whole new vocabulary with which to amaze our associates. We will hear more and more about such things as the intervals for 95 percent and 99 percent confidence, analysis of variance, regression analysis, replication, confounding, randomization, and interaction.

Before you plan your next welding test, enlist the help of a good statistician. You will find that the basic principals of any well planned experiment still apply. There is no substitute for precision. Neither statistics nor computers can make good data out of bad data. As in all well planned experiments we must establish the basic steps of procedure.

1. Specify exactly what is to be determined in each test.
2. Design the test to produce most reliable data that will be suitable for analysis (Statistical Design).
3. Outline the anticipated method of analysis. The response data must be in a form that is suitable for digital programming for computer analysis.
4. Take the data.
5. Analyze the results.

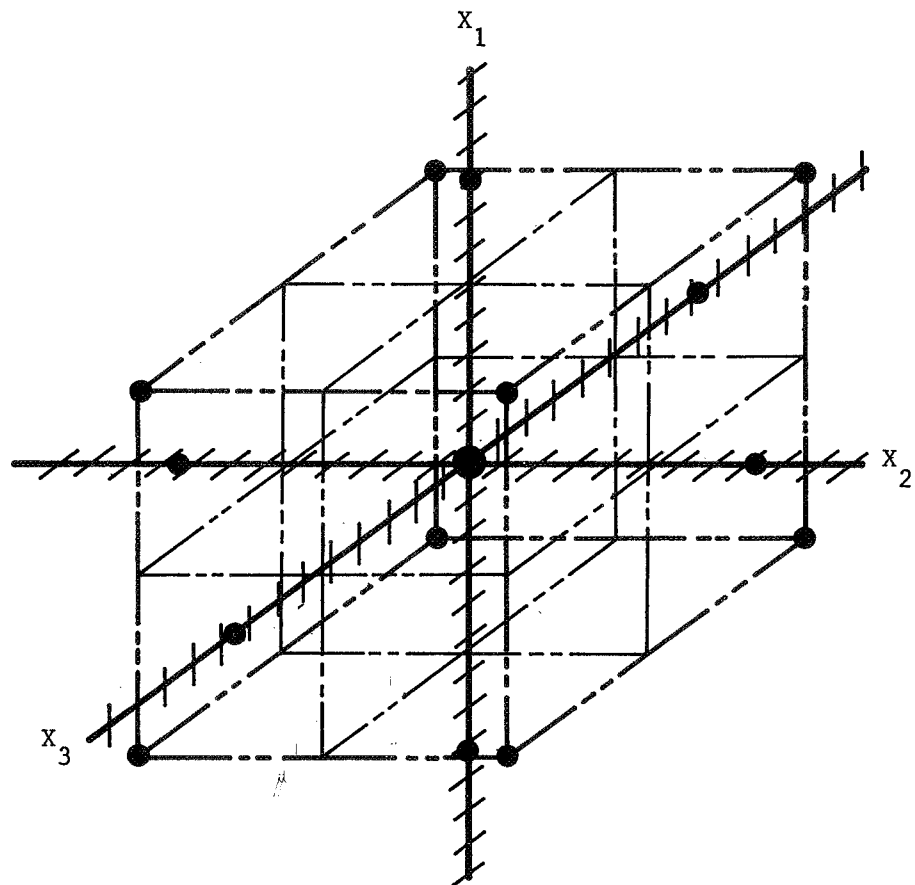


Figure 2. Data Points for Statistical Experiment Design with Three Variables.

For welding test at this time we are basically using only two statistical techniques. The Analysis of Variance technique is the simplest but widely used where we want to determine, with calculated mathematical precision, the effect of varying one or a number of the variables or in comparing two similar components of a system such as power supplies, or to establish the relative importance of a large number of welding variables. For analysis of the data from the analysis of variance we have an IBM 7094 program "General Analysis of Variance or Co-Variance" Lockheed-Georgia Deck No. 327400.

The second statistical technique that we are using is the Regression Analysis. This technique fits a line to your data points by the least squares technique and describes the line in the form of a quadratic equation. By using this technique the optimum combination of the settings of all of the welding variables may be arrived at quickly. For the analysis of this data we have an IBM 7094 program "Stepwise Multiple Correlation and Regression", Lockheed-Georgia Deck No. 3314.00.

It is our purpose to show that statistics can be used advantageously on the simplest of tests to produce much better and more reliable data at less cost. If we are able to consistently make a mechanized weld, we are ready to optimize and analyze our weld by using statistically designed and analyzed experiments. The basic mechanics of accomplishing this are as follows:

1. Design the experiment with help of statistician.
2. Run the weld test with as much precision and accuracy possible.
3. Record the data. This includes the variables of current, voltage, travel speed, wire feed, and others. The responses of tensile values, penetration depth, area, or any other response must be put in numerical form. For instance, porosity levels must be graded by number in order to be acceptable to the digital computer programs.
4. Select the proper computer program for the analysis of the data and fill out a data transmittal sheet. This is merely a clerical operation of transferring the welding data in the proper sequence for the particular computer program involved.
5. Make the computer run (Computer Operations).
6. Analyze the computer printout with your statistician.
7. Transfer equations and limits over which we are interested to data transmittal sheet for computer solution and printout of all the desired combinations (Clerical Operation).
8. Make computer run (Computer Operations) IBM computer program "Evaluation of General Quadratic Equations Involving N Independent Variables", Lockheed-Georgia Deck No. 3480.
9. Analyze print out from computer by scanning or by graphical presentation.

A new method of curve or surface presentation is being developed at Lockheed. By programming the regression analysis formula for three-dimensional plotting, it is possible to obtain from the X-Y platter an automatic visual, dimensional approach to understanding what responses the weld variables are producing.

Now we are in a position to tell the design engineer what the possibilities are as far as physical values of the weldment are concerned and ask him to tell us what particular value he wants for any particular design application. For example, when welding 2219 aluminum we find that the maximum ultimate strength does not coincide with the maximum yield strength or the optimum elongation. The computer output of our programmed data may be easily plotted for graphical presentation so that the design engineer and the welding engineer may easily choose the combination of physical responses desired and select the combination of welding variables to produce that result. (See Figures 3, 4, and 5.) The graphical presentations represent a series of curves or lines which form planes or surfaces of response. Previously we have been attempting to use simple curves for analysis that represent only one cross section of the entire response surface involved.

The statistics and computers have increased rather than decreased the burden of responsibility of the welding engineer to produce good, precise, and repeatable data. Fortunately, or unfortunately as the case may be, the computer reveals with mathematical precision, just how good our data are.

If there is any one key to good weld data, it is instrumentation. With good instrumentation and careful control of all of the variables, it is possible to utilize this new statistical computer tool to a maximum by transferring weld set-up data.

The conclusions from previous programs indicated several definite welding parameters that require considerable attention if we are able to transfer, with confidence, weld settings from machine to machine and from facility to facility. For example, we now realize that weld torch resistance, helium shielding gas quality, and tungsten electrodes are variables that must be accurately controlled. These items, and many others, that were previously thought to be constant, must be controlled with the same precision as the conventional variables of current, voltage, and weld travel speed. In each case it is necessary to determine the degree of control that we are able to maintain in comparison with the significance of each variable, and their interactions to the welding process.

Three erratic variables, previously thought to be constant, are welding torch resistance, shielding gas contamination, and tungsten electrodes.

#### Welding Torch

For ideal measurement of the welding arc, the voltage recorder leads should be connected to the electrode and the work as close to the arc as possible. This connection is not practical in the welding torch and the leads must be connected to the head of the body assembly. The recording then includes the voltage drop or IR drop in the welding torch barrel assembly, collet, and the electrode as well as the welding arc. The IR drop for welding torches has been measured to vary with different manufacturers by as much as .3 volts when welding at 500 amps.



Arc Current Amp $\pm$ 100	Arc Voltage Volts	Carriage Speed IPM	Elongation %	Penetration Overlap Inches	Ultimate Strength KSI
4.85000	12.50000	5.50000	-0.	0.06715	41.44957
4.90000	11.30000	3.50000	-0.	0.23919	43.45801
4.90000	11.30000	3.60000	-0.	0.02328	43.93910
4.90000	11.30000	3.70000	-0.	0.21736	44.37363
4.90000	11.30000	3.80000	-0.	0.20698	44.76158
4.90000	11.30000	3.90000	-0.	0.19696	45.10296
4.90000	11.30000	4.00000	-0.	0.18729	45.39776
4.90000	11.30000	4.10000	-0.	0.17798	45.64600
4.90000	11.30000	4.20000	-0.	0.16902	45.84766
4.90000	11.30000	4.30000	-0.	0.16042	46.00276
4.90000	11.30000	4.40000	-0.	0.15218	46.11128
4.90000	11.30000	4.50000	-0.	0.14429	46.17323
4.90000	11.30000	4.60000	-0.	0.13676	46.18861
4.90000	11.30000	4.70000	-0.	0.12958	46.15741
4.90000	11.30000	4.80000	-0.	0.12276	46.07965
4.90000	11.30000	4.90000	-0.	0.11630	45.95531
4.90000	11.30000	5.00000	-0.	0.11019	45.78440
4.90000	11.30000	5.10000	-0.	0.10444	45.56692
4.90000	11.30000	5.20000	-0.	0.09904	45.30287
4.90000	11.30000	5.30000	-0.	0.09400	44.99225
4.90000	11.30000	5.40000	-0.	0.08932	44.63606
4.90000	11.30000	5.50000	-0.	0.08499	44.23129
4.90000	11.40000	3.50000	-0.	0.24310	43.29219
4.90000	11.40000	3.60000	-0.	0.23180	43.77329
4.90000	11.40000	3.70000	-0.	0.22085	44.20781
4.90000	11.40000	3.80000	-0.	0.21026	44.59576
4.90000	11.40000	3.90000	-0.	0.20003	44.93714
4.90000	11.40000	4.00000	-0.	0.19015	45.23195
4.90000	11.40000	4.10000	-0.	0.18063	45.48018
4.90000	11.40000	4.20000	-0.	0.17146	45.68185

Figure 3. Section of a computer print-out showing predicted results of a TIG DCSP on one inch thick 2219-T87 aluminum alloy.

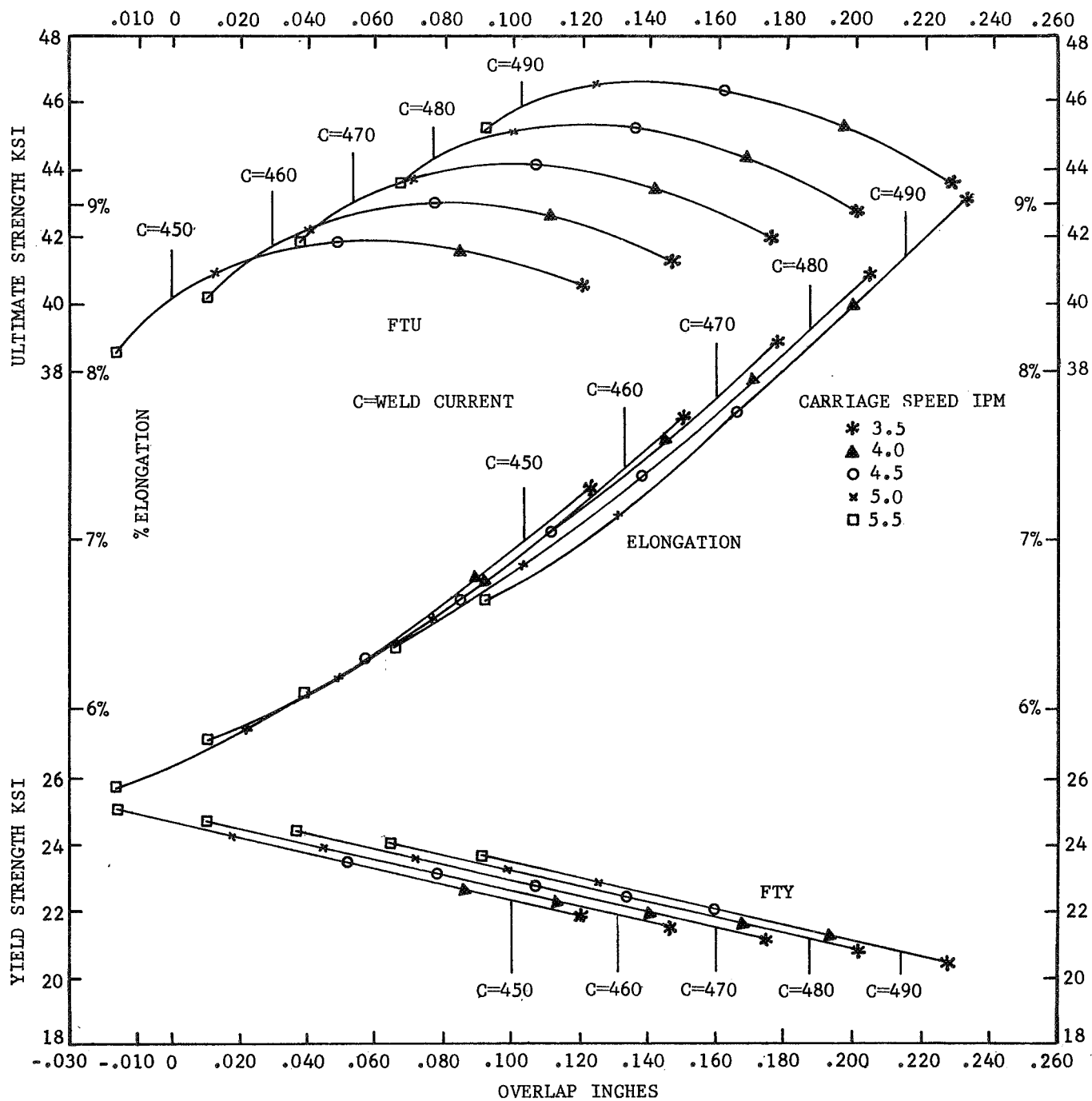
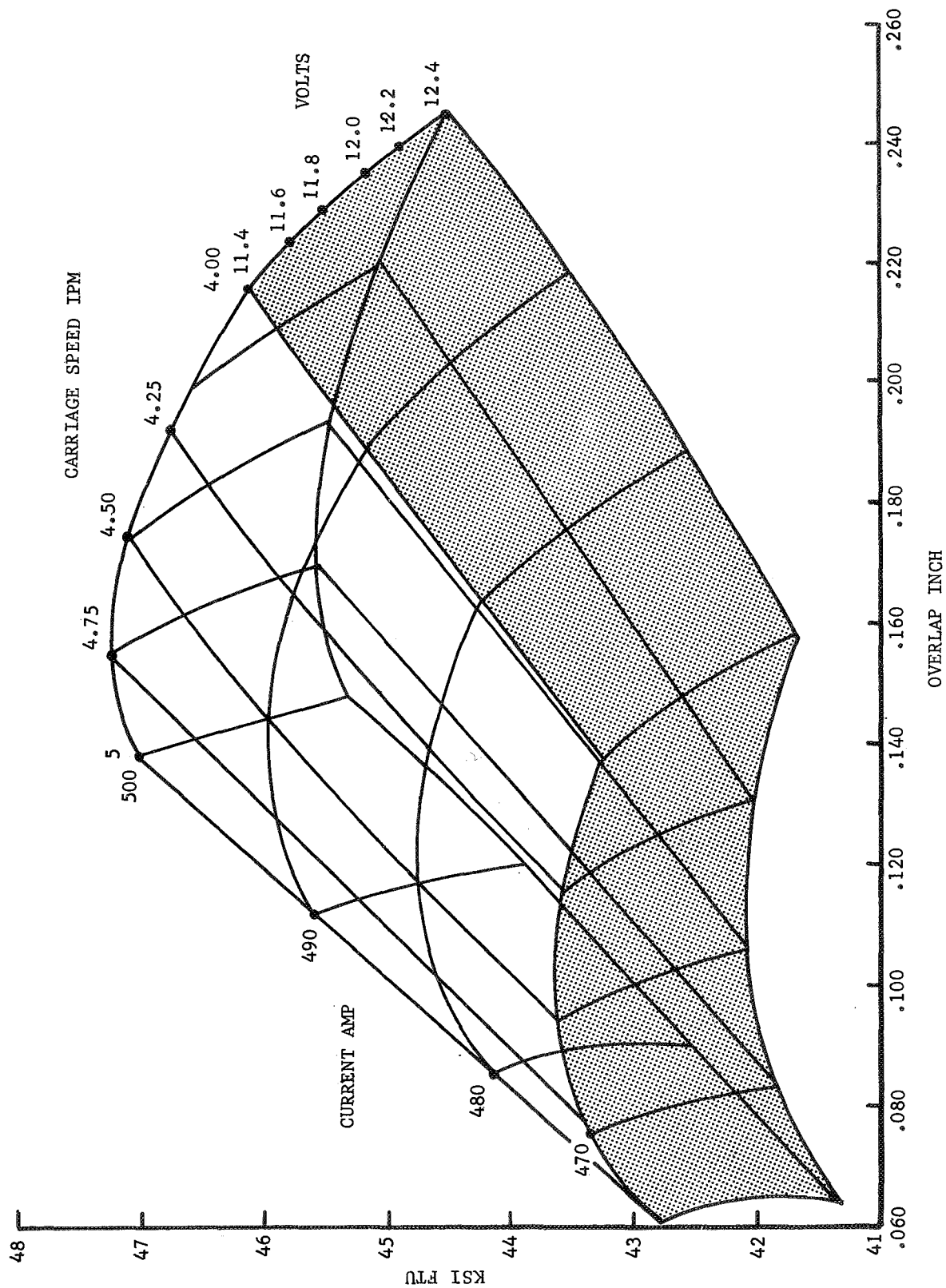


Figure 4. Predicted Welding Responses at 11.3 Volts.

2219 ALUMINUM ALLOY 1 INCH THICK



In anticipation of requirements for higher amperages and longer welding cycles, Lockheed has developed a gas tungsten arc torch capable of operating continuously at 1000 amperes. The water cooling system of this torch is completely brazed watertight, thus eliminating moisture leakage. The design is such that the IR drop is consistently below .080 volts at 500 amperes.

Variations in the TIG torch resistance will affect transferability of the weld set-up parameters. Preliminary tests on three torches and electrodes in the welding configuration show voltage drops ranging from a maximum of 0.647 volts to a minimum of 0.124 volts. In practice, this could produce an uncontrolled variation of 0.523 volts in the set-up parameters. From "The Development of Techniques for Multi-Pass Welding" (Nas 8-5334) project, the maximum and minimum voltage settings established for a square butt joint in one-inch thick 2219 aluminum alloy were 11.4 to 11.8 volts. With an allowable spread of only 0.4 volts, an uncontrolled variation of 0.523 volts will make these weld settings untransferable.

The electrical resistance from the tungsten electrode through the holding collet has been determined on TIG torches from three manufacturers. With 500 amperes passing through the torch, the millivolt drop across the collet was recorded using the Minneapolis-Honeywell Electronic 17 recorder. The variation in voltage drop was determined and recorded by repeated tightening and re-tightening the collets. The same tungsten electrode was used for all torches during a test series for standardization.

#### Shielding Gas

Variations from 67 to 263 part per million impurity in helium are being detected. Small changes in gas purity cause a change in the ionization potential of the shielding gas resulting in erratic changes in the welding arc voltage. High purity shielding gas is required to prevent metallurgical contamination of the weld, and consistent purity is required for a constant welding arc voltage control.

Another example of an uncontrolled variation affecting transferability of the weld parameters was evident in the helium shielding gas analysis tests conducted during previous projects. At intervals during the project, the voltage control became erratic. This was noticed particularly on the first weld after installing a new cylinder of helium. By welding with several cylinders "good" and "bad" cylinders of helium were isolated and subjected to analysis by chromatography flame photometer, infrared gas cell and CEC moisture monitor. The results showed impurity of 67 and 263 parts per million respectively for the "good" and "bad" gas.

A literature and correspondence survey has been conducted covering specifications, procedures for filling, and general information on helium shielding gas. From this study, revised purchase specifications were written for Lockheed-Georgia Company specifying no more than 50 ppm impurity.

### Tungsten Electrodes

The voltage drop caused by electrical resistance of the electrode has not been established. However, the resistance is known to change with temperature and when operating at incandescent temperatures this IR loss is a significant factor. Other characteristics of the electrode requiring consideration for uniformity are the tip configuration, surface condition, and metallurgy. Our pilot studies indicate a possible correlation between tungsten electrode density, emission stability, and weld quality.

The electrical resistance of the torch barrel and head assembly has been determined by using a dummy copper electrode and collet silver soldered as one unit. This unit offers very little electrical resistance. By this procedure we have been able to isolate and record the electrical resistance of the barrel.

### Moisture Monitor Test

It is suspected that the greatest harm caused by torch leakage is that minute leakage of water to the arc area is normally undetectable during the weld cycle. The moisture monitor could make possible a continuous sampling of shielding gas prior to, during, and after the weld cycle.

### Automatic TIG Welding Head

Weld head response speed should be analyzed by recording the tachometer feedback system of the automatic head simultaneously with the arc welding voltage and the arc length. A study of these three recordings may indicate a direction for improving the weld head control system.

Recordings should be examined for use in evaluation of automatic welding head control system using proximity controls in comparison to voltage control systems.

Weld puddle agitation is known to cause the welding arc voltage to fluctuate. With a slow head response the corrective action taken by the head is minimized. However, this allows the head and arc voltage to wander. An evaluation of recordings showing the arc voltage, length, speed of response and current with a fixed and an automatic head may determine the effects puddle agitation has on the welding control system.

Previous welding tests indicate that there is a minimum arc voltage at which the TIG automatic head will maintain control. When the arc voltage drops below the minimum, there is a definite loss of head control by "diving in" (See Figure 6.)

Once this point is determined, it may be used as a rough voltage calibration reference point. This can be very useful where the electrode is operating below the metal surface and no filler wire is used.

This minimum arc voltage point is known to change with different alloys but is believed to remain constant with each alloy and is not influenced by external resistance of the torch or electrode.

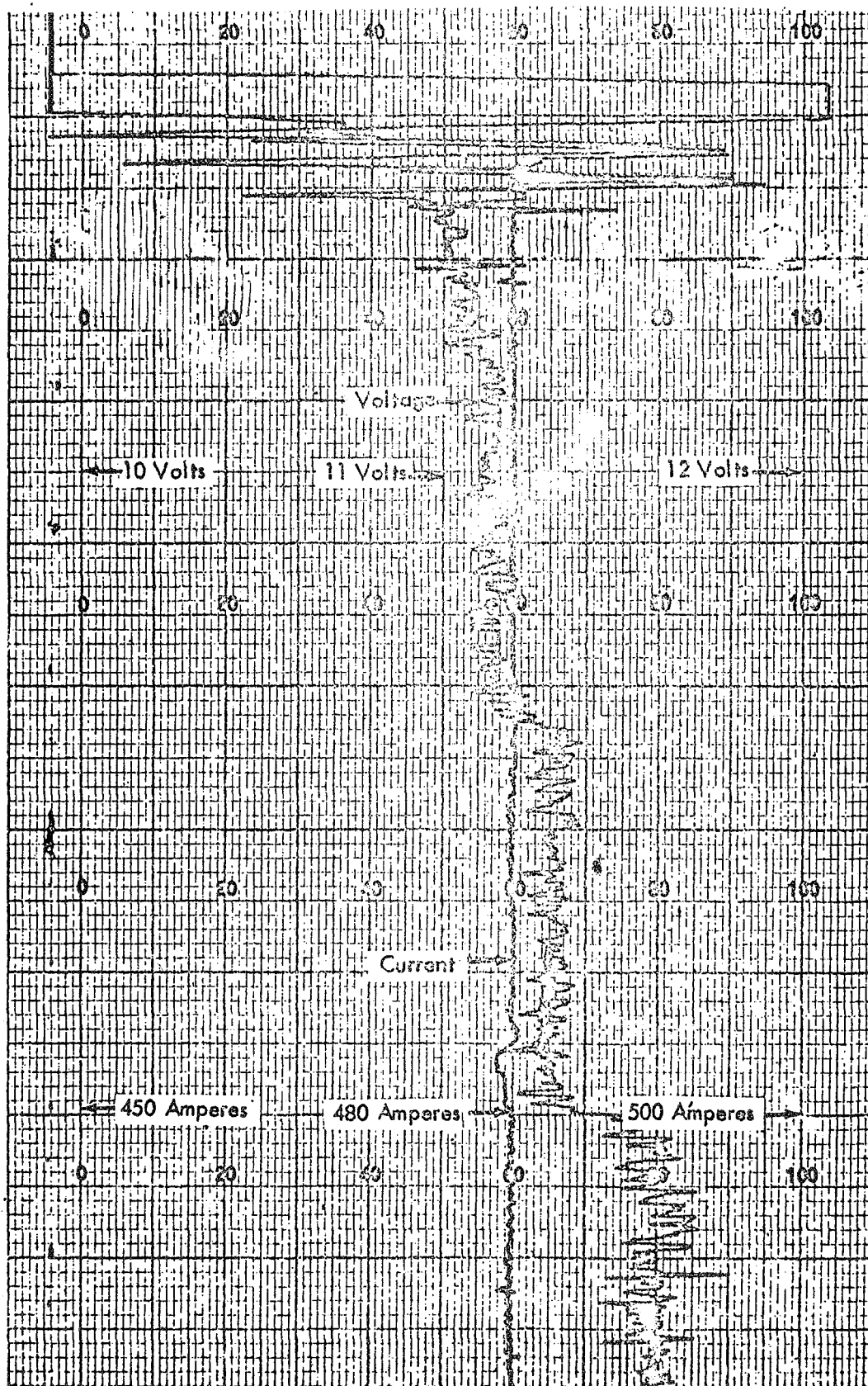


Figure 6. Typical Voltage - Ampere Trace from a Minneapolis-Honeywell Electronic 17 Recorder to Determine the Minimum Possible Operating Voltage. In this test the Current was Maintained at 480 Amperes and the Welding Voltage held at Test Levels of 11.6 Volts, 11.3 Volts and 11.15 Volts. At 11.0 Volts the Arc was Unstable and the Tungsten Shorted Out in the Weld Puddle. For this Test 11.0 was Determined to be the "Dive-in-Point".

### Carriage System

Carriage travel speed variations should be measured by recording the voltage output of the tachometer feedback generator. These data may be related to the distance traveled for a period of time for calibration of the recording instruments and accuracy of the carriage speed control system.

### Filler Wire Feed System

Filler wire speed may be monitored by recording of the voltage output of the tachometer feedback governor system. The length of wire consumed for a given period of time may be measured and used for speed calibration. A slow speed tachometer may be used to record and maintain wire speed.

### Environmental Factors

Variations in weldment surface conditions, and the resultant effects on weld quality, should be investigated by comparisons of hand filing versus scraping the weld joint prior to welding, using data from the two methods to determine the optimum method. This analysis may be accomplished by examining microphotos of the surface conditions and recording the resultant effects upon the arc voltage regulation.

### Weldment Temperature

The anticipated use of welding procedures using torches in tandem make it necessary to know and control the effect of preheating caused by the weld arc.

The temperature of the metal prior to welding is a variable that affects penetration, under-cutting, and, ultimately, the strength and transferability of the weld settings. We must anticipate the effect of this variable and to make compensating adjustments to the weld parameters.

Tests should be conducted to determine the significance of this weld variable.

### Weld Joint Fitup

Previous tests have been made to determine the effect of joint misalignment where one-half of the weld joint is raised above the plane of the opposite half of the workpiece. The effect of point separation caused by expansion and contraction of the workpiece when related to repeatability or transferability of weld settings must be investigated. It is believed that tolerances in joint fitup, tack welding, and expansion of the joint ahead of the arc contribute to an uneven preheating effect on the workpiece and therefore results in variation in penetration of the weld.

### MIG Welding Variable

The arc voltage - current-wire speed parameters cannot at present be transferred without compensations being made in one or more of the variables.

A major difficulty in transferability is measuring and recording the actual parameters of the arc itself. A method of accurately recording these variables at the arc instead of the contact tube must be devised. This also applied to the wire speed variations.

Prior to any welding or weld testing, the entire system should be thoroughly examined to make sure everything is in order. A weld set-up check off list may be useful for this purpose.



## DISCUSSION

Mr. Brown: I don't understand how you get these values; how you pick them?

Mr. Seay: What I have to do to get these values is say to the statistician, "Now, look we're getting ready to run the experiment and here is what I want to do." The first thing you have got to tell him is what it is you are trying to find out, and then you list the variables that you intend to vary. You see, in this experiment, you vary all the variables at the same time, and it uses all of the data on every computation. You and the statistician will determine how many variables you're dealing with and at which ones that you want to look. Then he will undoubtedly open up a text book and say, "Well, now, they publish a centrally composite rotatable design," if that's what he chooses to use. It will be listed, but these locations, these points, will be listed in the book as either 0, plus 1, minus 1, plus 1.414, or something on that order. You have to decide exactly how much 1 means to you, and how much 2 means to you. I chose, for instance, that 1 here would mean 10 amps. So, plus 1 would mean that I would go in the plus direction 10 amps. Minus 1, I would go in the minus direction 10 amps. All you have to do is transfer your values into these pluses and minuses that are already printed out in the experiment. Now the value of the statistician is that he can help you select the proper design to do what you want to do. The center of the rotatable design is the poorest when you know the most about the process. In other words, there are certain physical limitations here; when we get to 500 amps, we're in trouble. We know this physically; let's not confuse the computer. There's no need to make a design that is going to extend our data points up above the 500 line. This would be a composite design, but it wouldn't be rotatable. I would concentrate on a specific area that you want to investigate.

Mr. Seaman: I wondered if you would elaborate? Toward the end of your talk, you discussed some suspicions that you had of tungsten. Would you care to go on with this just a little further?

Mr. Seay: We started our work in this area, and ran tests, and we have gotten some data, but we have not done the part that I hope will give us the answers, and that's the metallurgical look. The centering process involved in making tungsten is something I know very little about at this point and time, but we have determined the specific gravity, weight, and density of various tungstens. We've got about four or five different manufacturers' tungstens. Here again, we are assuming that the batch we got is representative, but this is always the risk. We found a definite difference in the density of these tungstens. Under actual welding test, in order to eliminate the variables of having anything dip-in or transfer aluminum to the tungsten, we mounted another tungsten. The bottom tungsten, which was a quarter inch in diameter, was mounted in copper to dissipate the heat. We ran an endurance test, just let it blaze away at high amperage, and the bottom tungsten held up. We made our voltage trace on a Minneapolis-Honeywell trace recorder. Just by watching the voltage trace, you can tell a lot about what's happening in the tungsten---a good type trace and you've got good emission and good arc characteristics. When the trace begins to wobble, you can look at your arc, and you may or may not be able to see it.

Now, this is a real good point. I don't know whether I emphasized the importance of instrumentation or not, but I've got in our lab one of the old timers who has been welding for years. He learned the hard way, by hand; "instrumentation, who needs it?" But, today, this man does not look at the weld puddle except to monitor it. He makes his welds by watching that instrument. Because with the instrument, he can easily determine if he's lost 2 or 3 amps at 500, and it is significant. He can see when his voltage begins to wobble and look in and see what has happened, what has gone wrong, and he knows something has gone wrong. Carriage travel---he can hold his carriage travel now because we can hold carriage travel easily readable to plus or minus 1/10th in/min. We can easily read and control a voltage to plus or minus 5/10th of a volt. To hold current to 2 or 3 amps, it's necessary to continually be jiggling that dial, but you can do it, just 'as we had to do it in the old days when we did not have a functional control machine.

Mr. Seaman: Well, I wondered if you got around to the point where you saw any relationships, for example, in density and requirements according to trace?

Mr. Seay: No, some of the tungstens split, some of them melt down, and some of them flake off; all these things may happen. Some of them make good tracers from the beginning; some of them make sorry tracers from the beginning. Frankly, we have been snowed with other work, and we have that one sitting back waiting. But these things are happening, and I understand we have gotten the go ahead to take a real good look at them.

Miss Brennecke: Is this 2 percent thoriated tungsten?

Mr. Seay: Yes, that's what we're using, Hap.

AEROSPACE FUSION WELDING ANALYSIS  
AND CONTROL TECHNIQUES

By

R. A. Roen

THE MARTIN COMPANY  
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## INTRODUCTION

The present Aerospace structural criteria has revolutionized the welding industry by imposing requirements previously thought attainable only by utilizing the most rigid laboratory control conditions. As a result, extensive weld research has been conducted involving tools, equipment, alloys, and processes, with the ultimate goal being an efficient production welding process which would reliably produce the desired level of quality. The advancements from these programs have been quite rewarding; however, when the results are applied to actual production practice, many problems arise which we continue to blame on: equipment malfunction, tooling inadequacies, alloy deficiencies, and human variation. This continuation of production problems causes those of us in the line organizations to question if welding research has been adequate and properly directed; or on the other hand, if we have a thorough understanding of critical process elements and control necessary for a successful production welding operation? Obviously, some unbiased method of measurement and problem analysis must be utilized if answers to these questions are to be realized.

I would like to present the results of a study based on over 25,000 feet of aluminum fusion welding, designed to assist in analyzing production problems and corrective action. The paper will explain data collection techniques, methods of analysis, and process control indications developed and presently in use at the Martin Company, Aerospace Division, Denver, Colorado.

Table I is an example of the type of data collected:

Table I. Parameter Deck.

Column	Item	Variable	Code	Identification
37,38,39	Wire Feed Rate	M5	BXX	0 to 99 inches per min.
40,41,42	Head Travel	M6	BXX	0 to 99 inches per min.
43,44,45	Gas Flow	M7	BXX	0 to 99 cu. ft. hr. (no fractions)
46	Nozzle ID	N7	.1 2 3	3/8" 1/2" 5/8"
47	Gas Type Proportion	M8	B1 2 3	Helium Argon AG-75
48,49,50	Max Mismatch	N8	XXX	Maximum Mismatch in thousandths
51,52,53	Weldor	N1	BXX	Last two digits of Weldor's Stamp
54,55	Weld Machine and/or Fixture	N2	B0 1 2 3 4 5 6 7 8 9	-002 Fixture -213 Fixture -216 Fixture -024 Fixture -286 Fixture -218 Fixture -219 Fixture -221 Fixture -202 Fxiture -203 Fixture.
56	Wire Feed Diameter	N9	1 2 3 4	.030 .045 1/16 3/32
57,58,59	Gap	N3	BXXX	Gap in thousandths
60	Tungsten Diameter	M9	1 2 3 4 5	1/16 3/32 1/8 5/32 3/16
61,62,63	Temperature & Humidity	N4	XXXX	First 2 col. temp.
64				Second 2 col. humidity
65,66,67	Weld Start	N5	XXX	Inches from BLO
68,69,70	Weld Stop	N6	XXX	Inches from BLO
71,72,73	Max Thickness	L5	XXX	Maximum material thickness in thousandths
74,75,76	Min Thickness	L6	XXX	Minimum material thickness in thousandths
77,78,79	Location of Maximum Mismatch	MM1	XXX	Inches from BLO or Start of Weld

### Procedure For Data Collection

The completed list consists of 124 data points and variable recordings; however, some have been eliminated as being insignificant to the overall problem. The major portion of the desired data is available from the standard records and log books used in the fabrication operations; however, to supplement this study the following procedure for data collection has been initiated.

1. A Welding Engineer or Manufacturing Engineer is assigned to monitor each production weld set up. It is his responsibility to assure adherence to the process plan and that each parameter is accurately recorded on the proper form. At the end of each shift these data forms are collected and handled as described in Paragraph 3, below.
2. The responsible Engineer will monitor the results of hardware testing as it proceeds through all levels of acceptance testing. The Engineer will check all indications identified by these tests; those requiring repair will be documented by location, type, and disposition. The data will then be collected and handled as stated in Paragraph 3, below.
3. After collection, the data from Paragraphs 1 and 2 above will be coded onto an IBM transmittal sheet. These transmittal sheets will go to Administration where the information is key punched onto IBM cards. The cards are then retained in the data analysis file for historical reference. The program is organized so that the cards can be stored in any order without affecting their value. Programs are written for the computer to analyze based on the inputs contained on the data cards. In addition to the standard programs, specialized programs are written to answer questions such as "does porosity increase at a specific point on a certain article", or "which welder has the best defect record". Utilizing the data file and computers in this manner the program can be used by Engineers and Management as a knowledge source.

### Analysis and Corrective Action.

Once the basic body of welding knowledge has been collected and stored, simple process control indicators may be developed. An example of this is shown in Figure 1, an "Indication Per Unit" Chart. This chart is used to highlight the general quality trend.

The chart shows the number of indications picked up by all non-destructive test methods. This particular production run was reported bi-monthly and is used by supervision to measure the general weld quality level. The yearly goal in this case has been achieved by June 15<sup>th</sup>, or in half the time originally anticipated.

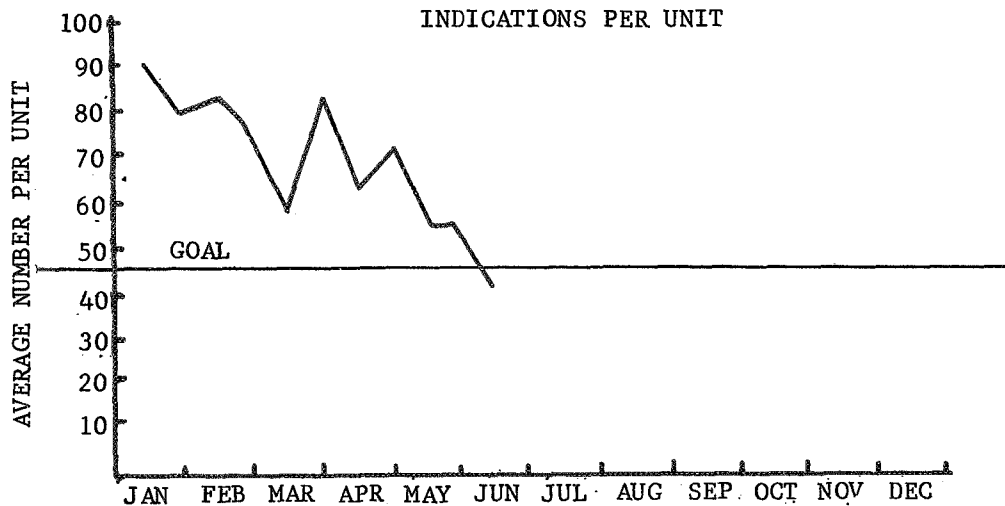


Figure 1.

Noting the variation of the number of indications totaled bi-weekly, we soon discovered Engineering criteria and Quality Control techniques had a definite influence on our analysis. The degree of influence is measured by the chart in Figure 2.

Since Quality Control must determine if a product does, in fact, meet the Engineering Criteria, some measurement of their accuracy seems pertinent. The items selected represent a Quality Control call out which later is determined to be within specification criteria. Engineering has the prime responsibility of developing criteria; therefore, the measurement selected for this chart represents how many times Engineering must be called into the evaluation with Quality Control to further define, or explain the acceptance criteria. The difference between the Engineering and total number of indications represents the number of items that were actually repaired.

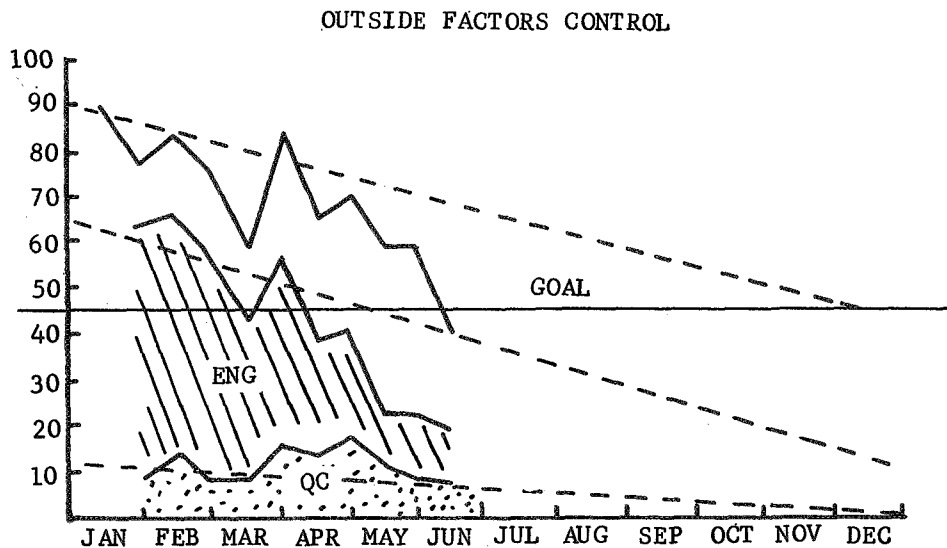


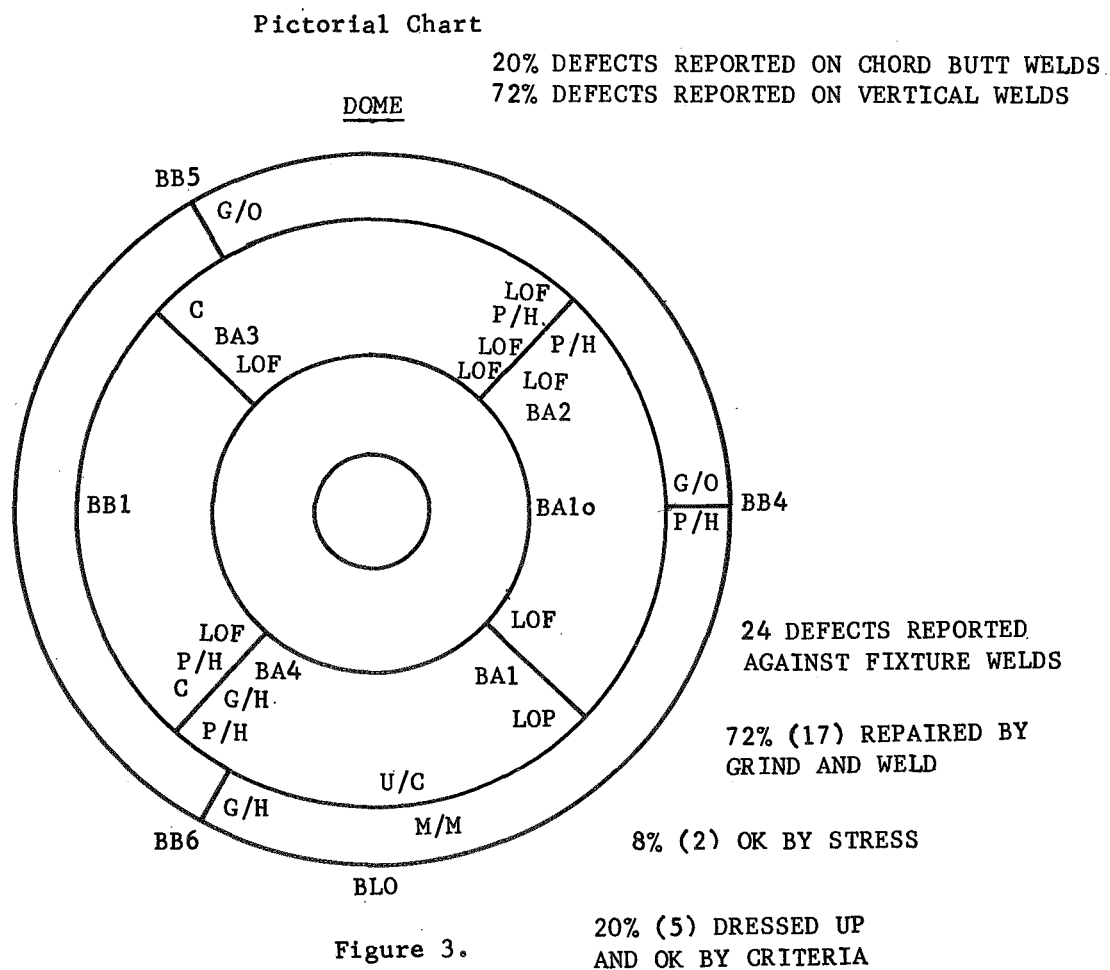
Figure 2.

By observing the relationship of Engineering and Quality Control measurements to the total recorded, it is possible to determine which area needs attention to improve the general trend. Examples: In February the high number of items that had to be reviewed by Engineering for final disposition indicated that either Engineering criteria was not adequately stated or Quality Control needed clarification. With this information at hand, both departments were informed and the resulting corrective action assisted in the downward trend of average total indications recorded against each unit.

In the case of March 15<sup>th</sup>, where average total indications reached 63 per unit, an analysis of the data was requested showing specific welds with a significantly higher defect rate than normal. The results indicated three areas which were subsequently analyzed and corrected; again assisting in the total downward trend.

Goals, as defined by the dotted lines, may be assigned for each department and measurements recorded to help point out where extra effort is required to achieve pre-determined objectives.

Although this type of indicator is valuable for the over-all trend, a more detailed chart (Figure 3) is used to analyze each component of the production unit.





By recording each indication accurately on the pictorial chart, like units may be overlayed and compared for repetitive defects. Further comparison after corrective action can confirm the effectiveness by following the actual trend from unit to unit.

Example: Barrel welds showed a repetitive low build-up at a certain footage on the barrel welding tool. On investigation, a tiny gouge was discovered on the back up bar in this area, causing the weldment to lose contact at this point, thus no heat dissipation and the resultant low bead build-up.

The pictorial presentation is also valuable in determining the effect of thickness, weld sequence, operator, equipment, and even alloy. By evaluation of similar conditions, historical back up data may be obtained which is necessary for Engineering design changes or criteria modifications.

Using the data developed from this study, a manufacturing welding operation can become an integrated portion of the master Company reliability plan. The measurement requires data collection on reliability sensitive items; such as, number of leaks detected by the helium leak test, failures in welds after Article acceptance, and so on. These critical items measurement must then be related to the reliability objectives required.

An example of this type of measurement is shown in the graph in Figure 4.

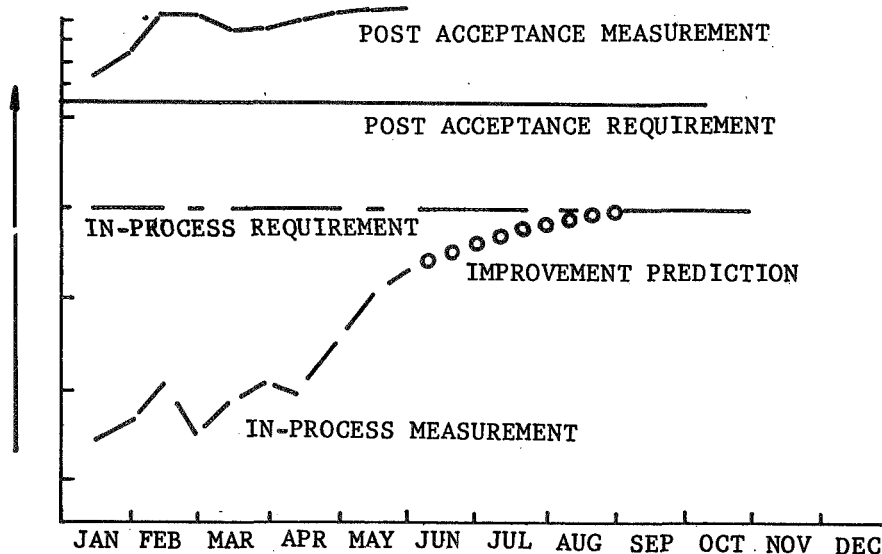


Figure 4.

The Post Acceptance Requirement defines the goal for Manufacturing Practice Reliability as set up on the over-all Company plan. The Post Acceptance Requirement is the actual number of failures termed reliability sensitive in the case of a welded product. The in process requirement defines a goal set up by Manufacturing Management measuring all indications, and defects recorded throughout the Manufacturing process. The in process measurement line tells how well we are actually doing in respect to our goal. Eventually, by comparing our process measurement with the Post Acceptance measurement, we will be able to predict the reliability effect from such indications as: number of total indications, number of weld repairs, and so on, depending on what provides the most valid information in terms of reliability.

## CONCLUSION

### The Human Element

The first eight months of this study confirm our previous suspicions in revealing the human element as a most important variable in the welding operation. The human element, (those variations from operator to operator, as well as interpretation of non-destructive testing techniques and Engineering criteria) can account for as much as 85 percent of the total welding problem. When this variable is recognized and a concerted effort is extended, the weld problem can be reduced considerably (theoretically, 85 percent) without further investment in new welding tools, equipment, or design changes.

### The Effect of Equipment and Tooling

By utilizing the pictorial charts and measuring the repetitive type defects, we may assume a 12 percent contribution to the total weld problem caused by equipment variation and tool deficiencies. Corrective action in this area can be as simple as the example of the gouge in the back up bar on our barrel weld tool; or as extensive as a recommendation for a complete new tool involving considerable expenditures. A little ingenuity can usually solve the problem, once the difficulty is known.

### The Effect of the Alloy

In the few cases where no logical explanation for weld defects or defect indication could be given, the cause was assigned to the alloy. This amounted to 3 percent of the total and is justified by the assumption that no alloy is 100 percent weldable.

NOTE: By further analysis the above factors may be broken down into more specific problem areas which become highly sensitive to conditions unique to certain contracts, facilities, and design; therefore, the data is not considered pertinent to this audience at the present time. It must also be noted that the percentages expressed can be considered valid for only one set of conditions over a very limited span of time. As improvement is realized the percentage of contributions for each factor change.

This method of data collection, control, and corrective action is an essential part of a successful Aerospace welding program. The techniques are adaptable to any welding situation and will prove a valuable tool for both Customer and Contractor.

## DISCUSSION

Mr. Ingram: We thank you very kindly. We are ready for questions, and I am quite certain that you have provided a few.

Mr. Orr: There is one I would like to ask, if I may. Do you relate your schedule to this, for instance, on your education chart there? In some months you might have a release of parts, perhaps a real tough elbow or something very difficult to weld, and for the next month that elbow might not even be manufactured. This is a point.

Mr. Roen: It certainly is a point, and that's part of Ed Seay's confounding. Fortunately, most of the study was done during a production area where we could keep a fairly good flow going through the various places. That's one problem with welding launch vehicles. You want one this month and three months later you want another one. You can't get a feel of this. But the ones that we have been able to follow have been fairly consistent. We have kind of put that in the background as a major factor in this analysis. There's a lot of guess work in this, admittedly. I've been out in the manufacturing line operation now for eight months, and I'll tell you, I respect these people for their feeling without laboratory backup or anything. I certainly respect their knowledge. They'll say, "If you do it that way, you're going to be in trouble." They can't explain why, but sure enough I get in trouble. So, there's something in this that you can't just substantiate by laboratory test. But that has been a problem.

Mr. Blackburn: You kind of stunned me a little bit with your 85 percent people problem. I'd like a little bit more clarification. First of all, let me say I assume you must be talking about manual welding. Whether you are or not, do you attribute this to lack of knowledge, lack of skill, lack of training, or lack of concern on the operator's part; because if it's any one of these four, I can assume that you can solve 85 percent of your problem by a concentrated training program.

Mr. Roen: Training is a very important part. Our welding from the study was 99 percent automatic, a very small percentage manual. We have found in this human element that the variable, the biggest variable that I feel is in the business, is in the interpretation of criteria, specifications, and the operator to operator variance. We found this in a porosity study. One guy will call it level P4, as one case; another guy will look at it the next day, and say, "No, it's P2." This thing does exist. I think we all recognize it. But that, being one part of the story, is a quality control and a criteria problem for them to work on and get their specifications clearly defined, so that you can operate successfully without this garbage in between. The other part of it is an operator problem. Such things as simple as automatic sequence start; we found that our people were even misusing that. Now, that's pretty basic. You press a button, and it starts. How can you ever misuse something that simple? But we misused it. We found people that had their own personalized touch on this start. Maybe they wanted to just regulate wire feed all by themselves. I was a little amazed myself at the 85 percent figure, but I think now it is not quite high enough. Without going into a awful lot of detail, I guess I couldn't convince you anymore than I have just done. It gets

down into the specifics of the contract where you add the type of alloy, the type of tooling (hard tooling, opposed to soft tooling), that sort of thing. But, again, it's in many cases, a guess.

Mr. Saperstein: What about sensitivity of the inspection method which you have implied?

Mr. Roen: Boy, that's a bomb. You hit a real item there, Phil. Watch it, watch the system, and keep your finger on the pulse. When you have a failure, and let's say you pin the failure back to a specific cause such as porosity crack or lack of fusion, watch what the people in inspection do; and I would do it to, to be truthful about it. They will not pass a single indication like that for an awful long time because they are not going to get clobbered or have that indication come back on them, and someone say, "Hey, you missed this. So, you are the cause of this failure." The biggest cause of this type of problem is the fillet weld, and we're always confused with "Is that a crack down in that root, or is that just lack of penetration or lack of fusion, or what is it?" So, to be safe, the man will call it a crack. Because if it is truly a crack that causes a failure and he doesn't call it a crack, he can get pinned down with this problem. That's been a real tiger to get a hold on. We try in our training and by close supervision---by instructing the people, which you brought up---that if they get one that's on the fence, to call in the supervisor, and let him make the decision. That's what he's getting paid for.

Mr. Saperstein: The most refined inspection in some respects in crude.

Mr. Roen: Yes, such things as density in film and the die penetrant area where you have the amount of time that you let it absorb into the material; I suppose that if you do a real good job in washing it off, you get less indications; if you don't do a good job, you get more indications. Is this what you are talking about?

Mr. Saperstein: I'll make it more definite. Recently, we looked at the sensitivity of some of the inspection procedures and simulated the total lack of fusion defect in the weld. None of these special methods we have employed were able to detect this total lack of fusion defect. This includes all types of inspection, dye penetrant, radiographic, and other inspections. The only way we could see it was by looking at it, and this is not always possible.

Mr. Roen: Yes, frankly, I haven't done any work in that area for quite some time. But I sure recognize the problem you're talking about. I have no other comment than that, though.

Mr. Ingram: No other questions?

Mr. Devins, There is one thing that troubles me about your first plot. After you are through adding the blue and the red to the yellow area there, it doesn't seem to change. Does this mean that there's still no improvement in the overall number of defects in the last six months, or what does it mean?

Mr. Roen: Actually, I think you've right. We have not improved in that one area, which is quite a cause for concern. And this has been my fear all along that eventually I'm going to end up on a plateau. And when I hit this plateau, then what am I going to show that's good? So, again, these are areas we're just starting to get a handle on. But if you don't find it, you certainly can't work on it. So our approach so far has been to recognize the problem and then get to work on it.

Mr. Ingram: One more question?

Mr. Seaman: Just for my own clarification, in the percentages which you gave in your conclusions, 85 and 12 percent, I noticed that the 12 percent was selected by defining tooling more or less as repetitive symptoms. I'm assuming that the 85 percent then was basically non-repetitive. It's inherent, somewhat relatable to human mistakes. I'm not quite sure how you get the 85 percent.

Mr. Roen: Yes, it's a good question. Our approach to it, the way we define it as a human element, is really after the corrective action has been taken to make sure that we have taken such action. You can also find this by running the chart the next month to see if you have corrected a repetitive type defect or a human problem you have found. A case of this would be the welder who was twice as good as one that we had on the night shift. When we got back to the man on the night shift, we found simply that he was not preparing his edge properly. He was doing everything up to that point, but when he did the process, he was a little bit careless in his edge preparation; so, therefore, he had twice as many defects as any of the other welders. We instructed him in the proper procedure -- left the welding engineer there - showed him how to do it, and the next month that human element, as I call it, disappeared. This man was then doing his job properly, so to speak, and so it did disappear. Again, it's a little touchy when you try to separate these and be very specific in calling this a human element and this a tool and equipment problem. Actually, they are quite interrelated. The ability of a person to handle all three at one time is difficult.

Mr. Wuenschel: In order to clarify where you are with your theory, I think we have to consider how far you have gone down the learning curve of that specific production. For obviously, you are not talking about the prototype development phase nor about the process development and verification phase. You talk about something where you are already so far down the learning curve that in reaching that plateau you are on a level where your equipment is more or less close to a perfect state-of-the-art. What's left over can be nothing else but human influences. I think it makes all the difference whether you talk about a type of line item production, which has run a long time and you are close to perfect in your mechanical setup, or whether you have just finished a development phase and you still have a lot of improvement to introduce.

Mr. Roen: Yes, I wish I would have included that in my paper. That was very well stated. We've been using this for seven years now. It's very true. When you're coming down on your learning curve, it's really difficult to tell whether it's a human element, a tooling element, etc. Although I do believe by this type of analysis it would help, even in the learning curve

area, to vary the top portion where you are starting to come down. We are using this on our Titan III. It's working out quite well. We are able to make corrective action and show an improvement from these figures, quite dramatically in some cases. It's a very good point. I'm glad you brought that up.

Mr. Wuenscher: Otherwise, it would be hopeless for weld equipment developers to have some business.

Mr. Roen: Oh, yes. I believe they've done a tremendous job though, and actually, they have potential in equipment and recent developments that we haven't even touched in the line operations. We don't quite know how to cope with these things yet. They're new to us.

Mr. Gaw: By way of clarification of your equipment and tooling categories, would you estimate for the record the average age of the welding heads which you are using.

Mr. Roen: Well, the age in that category would be from a year and a half to two years, because as we have gone up in thickness, of course, we have had to get more. We've had to buy new power supplies to get the amperage ratings that we needed.

Mr. Gaw: Your equipment is no more than two years old then?

Mr. Roen: The welding equipment itself, yes. The tools and fixtures are about seven years old and have been modified several times.

ALUMINUM FABRICATION  
VERSUS  
ENVIRONMENTAL HUMIDITY

By

Hiram Brown

TRW ELECTROMECHANICAL DIVISION  
THOMPSON RAMO WOOLDRIDGE INC.  
CLEVELAND, OHIO



## Aluminum Fabrication vs. Environmental Humidity

Any metal which is fusion welded goes through a molten phase so that, in effect, the weld is essentially a casting in which heating and cooling occur in a manner which differs from that of normal casting. Heating and cooling rates are faster, and metal temperature is higher. However, since molten metal is involved it may be informative to review the work that has been done concerning the causes and effects of gas porosity in cast aluminum, in the hope that some correlation with weld porosity may be found.

### Cause of Gas Porosity

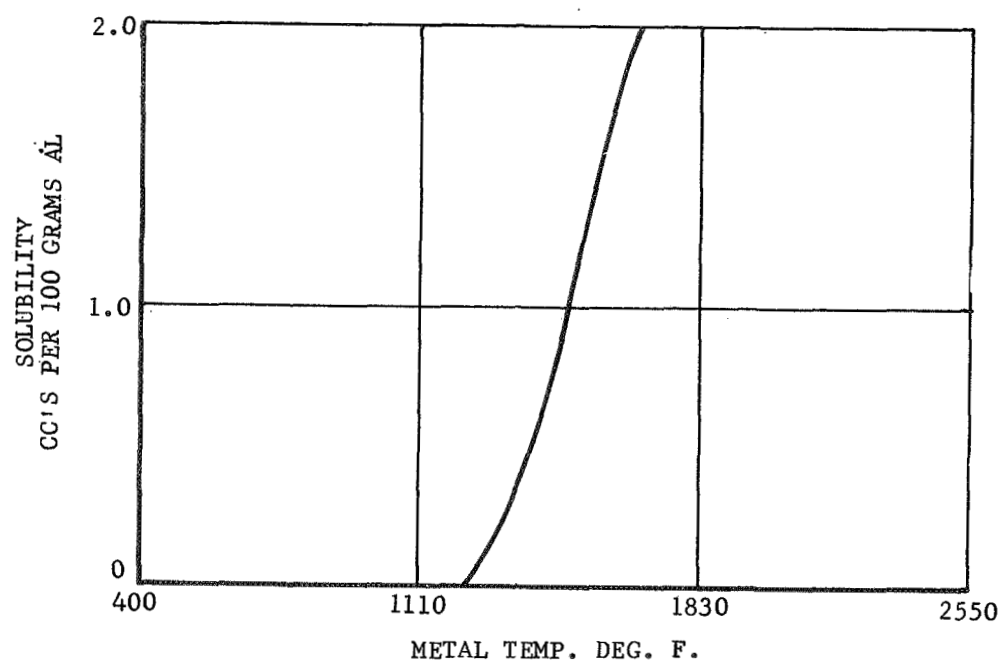
The major culprit insofar as gas porosity is concerned is generally conceded to be hydrogen. Since hydrogen is soluble in molten aluminum and practically insoluble in solid aluminum, any hydrogen present at time of solidification will be rejected in the form of porosity as the metal solidifies. Figure 1 shows that the solubility of hydrogen in molten aluminum increases as metal temperature increases. Of particular significance is the fact that the solubility of hydrogen in aluminum is for all intents and purposes practically zero the minute the metal solidifies.

The hydrogen normally comes from water vapor. At temperatures above 920° F aluminum reacts with water to produce nascent hydrogen plus oxygen. The hydrogen dissolves in molten aluminum and the oxygen combines with aluminum to form aluminum oxide. The water vapor may come from two sources: (1) the ambient atmosphere, or (2) adsorbed layer on the oxidized metal surface. Aluminum rapidly forms a thin oxide layer when exposed to air, and this layer will adsorb moisture. To visualize how this can occur, just think about aluminum cafeteria trays that have not been properly anodized and sealed. If these rub against a white shirt, a black streak is visible. This is because porous oxide coatings will pick up extraneous matter, including grease, stains, etc., and retain them in the pores as an adsorbed layer.

The presence of water vapor in the atmosphere is a very complex problem. For one thing, it varies with seasons. The higher the humidity, the higher the water content in the air. However, the relative humidity, which is that usually reported by the weather bureau, is not the true criterion. Relative humidity is merely a percentage which expresses the ratio between the amount of water present in the atmosphere and the amount of water vapor that is needed to saturate the air at the particular temperature at which the reading is taken. Naturally, the warmer the air, the more moisture it can absorb before saturation is reached. As an example, 50 percent relative humidity at 40° F represents much less actual water content than 50 percent humidity at 95° F. Therefore, absolute humidity is the measurement which must be used. This indicates how many grains of water per cubic foot of air are actually present at any given time.

An example of how absolute humidity is determined is shown by Figure 2. To obtain the basic information, readings must be taken simultaneously on two thermometers. One reads the actual temperature. The other has a

Figure 1. Solubility of Hydrogen in Molten Aluminum



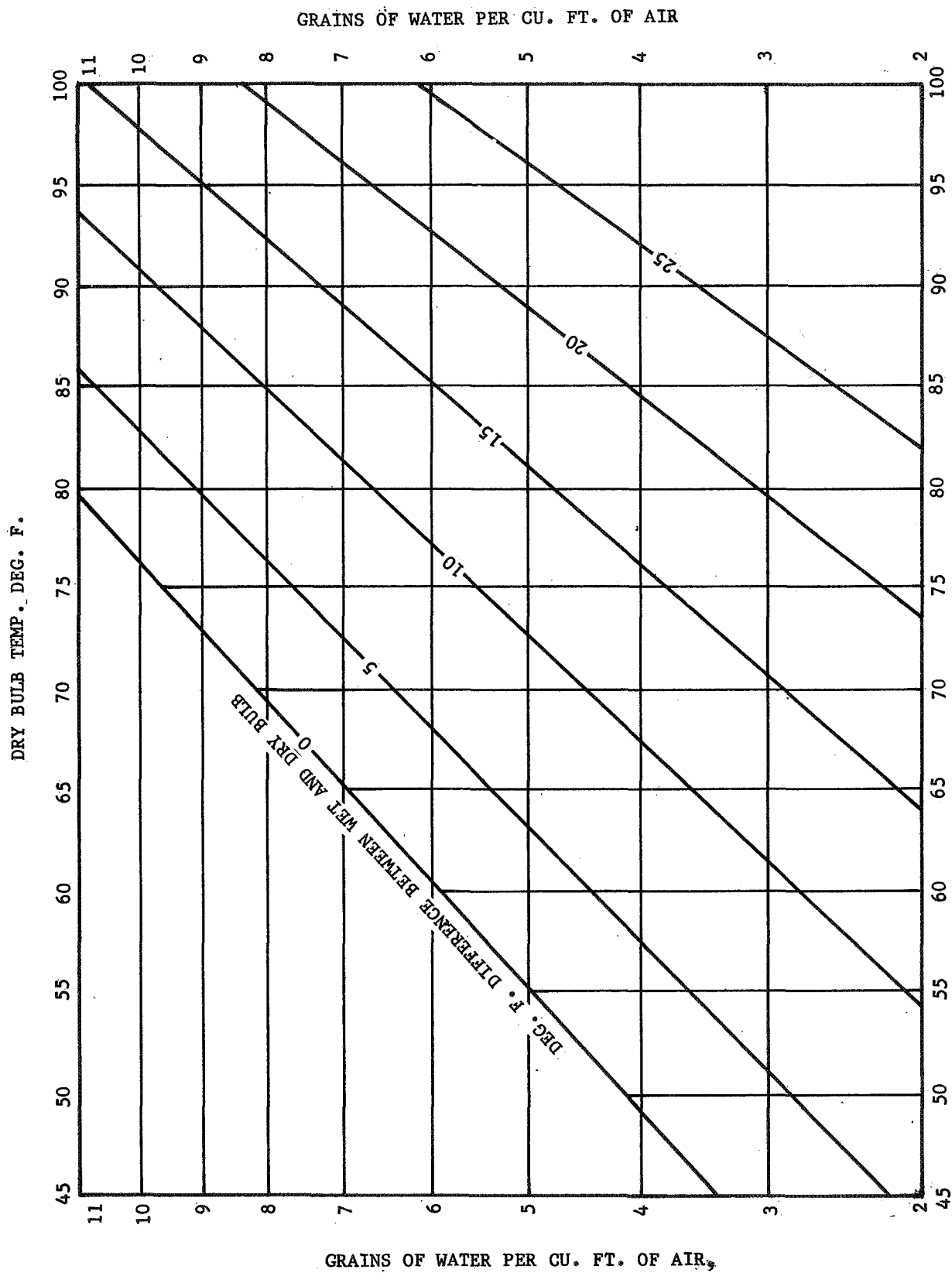


Figure 2. Absolute Humidity

wick arrangement attached to the bulb. As air is caused to move over the wet bulb thermometer (by use of sling psychrometer or other means of air movement), evaporation takes place. Evaporation tends to lower the temperature reading. The greater the evaporation rate, the less humid the air and the greater the difference in readings between the wet and dry bulb thermometers. By noting the two readings and referring to the chart, the actual grains of moisture per cubic foot of air can be designated.

Another potential source of hydrogen that should be explored is the as received material itself. It should be determined whether hydrogen is present in the base metal. Could it be trapped in inclusions, or in segregated areas of elements which have high solubility for hydrogen? I don't believe that we know too much about these possibilities.

Still another potential source of hydrogen which should not be overlooked is the presence of grease or other hydrocarbons. Contamination with such compounds should be avoided.

#### How Porosity Occurs

Gas porosity manifests itself in three ways: (1) pinhole porosity, (2) microporosity, and (3) a combination of (1) and (2). Pinhole is so-called because it occurs as scattered round or angular holes visible to the eye on a machined surface and is easily detectable by Xray. Microporosity is fine, difficult to detect visually, and on Xray film gives a mottled appearance which might be confused with the mottling caused by grain size. Which type of porosity forms is dependent upon the alloy composition and solidification characteristics, as will be discussed later.

Pinhole porosity has a serious effect on ductility, fatigue life and corrosion resistance. Its effect on tensile properties is much less pronounced. Microporosity not only has the same deleterious effects, but may cause reduced tensile properties, and if "channel" porosity forms, can cause the part to be porous.

#### Effect of Alloying Content on Type of Porosity

Alloying elements tend to influence porosity formation in two ways: (1) by affecting solubility of hydrogen in the matrix, and (2) by affecting the solidification range of the alloys.

Copper -- When copper is present in amounts over 3 percent, the solubility of hydrogen in aluminum is markedly reduced.

Silicon acts in a similar manner.

Manganese and nickel reduce absorption of hydrogen and cause it to be retained in solid solution.

Magnesium additions considerably increase the solubility of hydrogen in aluminum, and the presence of 6 percent magnesium almost doubles the solubility.

The total composition affects the solidification range of any particular alloy, and thus influences porosity. In general, aluminum alloys fall into three categories insofar as solidification is concerned:

- A-- Solid solution types which solidify over a wide range of temperature with little or no eutectics; e.g., Al-Mg and Al-Zn-Mg alloys.
- B-- Alloys solidifying over a fairly wide range of temperature with a small amount of eutectics; e.g., Al-Cu-Si alloys.
- C-- Alloys solidifying over a wide range of temperature with a large amount of eutectics; e.g., Al-Si-Cu alloys.

Type A has practically no tendency to form pinhole porosity, but does form microporosity. Type C tends to form pinhole porosity with very little microporosity. Type B is intermediate and will contain pinhole porosity grading into microporosity.

#### Effect of Solidification Range on Porosity

Cooling rate is an anomalous subject. If metal is heated considerably above the melting point, hydrogen can be absorbed into the molten metal. (See figure 1.) Slow cooling to just above the freezing point will give a more gas free cast structure than one cast from the same metal at a higher temperature. Rapid cooling will trap more gas; however, the porosity may be harder to see since it will be more finely divided and scattered. A slow cool until the solidification temperature is reached, followed by a rapid cool thereafter should give the best results.

#### Minimizing Porosity

It goes without saying that presence of hydrogen should be avoided as much as possible around molten aluminum. Several methods of prevention have been tried in the foundry industry:

- 1-- Handling molten metal in a humidity controlled room. Effort should be made to keep moisture as low as possible, preferably under 2 grains per cubic foot of air.
- 2-- Metal which has been exposed to air and moisture--as in normal ambient conditions--is dried to remove adsorbed moisture before melting the metal.

A common preventive measure is to degas the molten metal with gaseous chlorine or a degassing salt flux.

Because of the speed at which reactions occur in welding, it is difficult to make direct comparison with those occurring during casting. However, many of the basic principles would be expected to hold. Perhaps attention should be given to controlled atmosphere during welding and/or use of chlorine or degassing flux during the welding operation as means of minimizing problems resulting from gas porosity.

## DISCUSSION

Mr. Chyle: Thank you, Mr. Brown. We're sorry for the difficulty and the handicaps you were under this morning. Did we hear something about a reliability factor yesterday? Well, in the interest of saving time, we are ready for discussion and questions from the floor. Who has the first question? Yes, Perry? Perry Rieppel from Battelle.

Mr. Rieppel: Why do you think that if you weld in an air-conditioned room you would cut down on porosity?

Mr. Brown: I said it should be considered because we found in dealing with molten metal in the foundry that air-conditioning and taking out the humidity did result in gas-free products.

Mr. Rieppel: Then, if this were true, you would have to assume that something went haywire with the shielding of the weld. Otherwise, there would be no problem.

Mr. Brown: Mr. Rieppel, I do not think there is any doubt. That things go wrong with the puddle. That's why I think you ought to give every precaution you can to the man that has to produce the weld. He's living on a ragged edge when he hasn't got it.

Mr. Chyle: Yes, Nick Racktivitch.

Mr. Racktivitch: Mr. Brown, did you add boron trichloride in your gases in the molten metal?

Mr. Brown: Yes, it was very effective.

Question: Would you anticipate any toxicity problem?

Mr. Brown: Anytime you're using chlorine products around molten metal, there's going to be a toxicity problem. First of all, you must make sure you have an immersion and that the outlet holes for whatever tube you are using are completely immersed in the metal. Also, you must have a hood for venting.

Mr. Chyle: I'd like to offer a comment. You haven't said anything this morning about the moisture in your argon gas. Have you looked into that phase of the test? So far, you've been talking about the ambient atmosphere, haven't you? What about investigating the moisture in your inert gas?

Mr. Brown: That was what I would consider to be ambient atmosphere for welding. We found many times in the past, particularly in titanium welding, and I'm sure that all of you agree, that unless we purify those gases as we receive them, we are usually in trouble. There is no question that there are contaminants in those gases that we receive.

Mr. Chyle: I believe there's a paper going around that will have a bearing on this factor, Monitoring the Purity of the Inert Gases. Are there any other questions at this time? Yes, this gentleman over there.

Mr. Civello: Often it is possible to make a completely porosity-free weld. When we repeat this weld, all parameters and all conditions being equal, suddenly we have porosity. In other words, it's not reproducible. Why can't we control it? Why is it that one time we have a good weld, and the next time we have micro porosity, or scattered porosity?

Mr. Brown: In the first place, I think you served me a curve with the very fallacious statement of your question. You said, "All other factors being equal." If you had everything else protected and everything was equal, there is no reason why it would not reproduce. But somewhere along the line, you're missing something. And this may not only be in your weld; it may be in your base metal. Don't forget, I said take a look at that, too. I'm not convinced in my own mind that some of these segregations of materials which have a high solubility for hydrogen can't cause you trouble in your welding operation.

Mr. Chyle: I'd like to ask this question. So far, this has been entirely on hydrogen in aluminum. Are we sure that there aren't any other gases, such as nitrogen, that might be culprits too? Is nitrogen definitely ruled out?

Mr. Brown: We use nitrogen as a degasser to take out hydrogen in many heats and you never find any deleterious effects. It's almost impossible to trap it in there. If nitrogen does react in any way, all it does normally is make a little grain refinement with it's carbon or something else that's present. There's been no problem as far as I know.

Mr. Chyle: Well, gentlemen, we could continue but our time is running out. In order to give the other speakers ample time, I'd like to thank you, Mr. Brown, for a very interesting paper, and I'll turn this over to Jim Orr who will introduce the next speaker.

Mr. Orr: The next symposium we have will be on the reliability of projectors.

WELD DEFECTS IN ALUMINUM  
VERSUS  
BASE-PLATE AND FILLER-WIRE COMPOSITION

By

P. J. Rieppel

BATTELE MEMORIAL INSTITUTE  
COLUMBUS, OHIO



## INTRODUCTION

Porosity and cracking in weld joints have been serious problems as long as fusion welding of aluminum has been practiced. These weld defects have grown more and more important as higher and higher strength alloys have been developed and used in all-welded, all-aluminum high-performance structures. The Saturn first-stage booster is a typical application.

The TIG welding process was being used quite extensively when the MIG welding process was developed in 1946. Porosity was a problem in TIG welds in aluminum but not so severe as it had been earlier in oxyhydrogen, oxyacetylene, and atomic-hydrogen welds. The early MIG welds were very porous. It was necessary to do something to reduce porosity before these welds could be considered of much value.

Considerable information was available concerning the role of hydrogen in producing porosity in aluminum castings and aluminum oxyhydrogen and oxyacetylene welds. The obvious things to do were to remove the surface oxide layers from the MIG welding wire and the surface of the weld joint just prior to welding. This was done and immediately the major part of the porosity problem was solved. Much work has been done since on methods of removing and controlling the surfaces of aluminum base plate and MIG and TIG welding wires but the basic solution to the porosity problem has remained about the same.

It also was learned in 1946 that very efficient shielding against air and its water-vapor content was necessary in order to produce sound welds. If the slightest amount of humid air was permitted to contact the molten aluminum weld pool, porosity increased. Also, water vapor or hydrogen from any source such as shielding gases or faulty equipment had to be eliminated, or the porosity increased. When all of these obvious precautions were taken, 95 percent of the porosity was eliminated nearly all of the time. This "phantom" cause of porosity of 1946 is still around. Basically, very little progress has been made in freeing aluminum welders from the problem.

In 1946, after everything that seemed reasonable had been done in terms of cleaning the wire and plate surfaces, providing an efficient shield of pure dry gas, several experiments were performed in a closed welding chamber. The chamber was filled with high-purity and very dry argon, and the surfaces of the filler wire and base plate were removed mechanically in this chamber. Welds were made in the chamber with the freshly cleaned wire and plate. However, in spite of all precautions, porous welds would come along when least expected. All sources of hydrogen other than that contained within the plate and wire were believed eliminated. The welds contained too much porosity to meet very high standards. It was concluded that the hydrogen came from the base plate and/or the wire.

In 1964 the battle with "too much" porosity in very high-quality welds for the Saturn booster and other structures still goes on. First, we see it, then we don't. When it suddenly appears - what may have caused it? It could be:

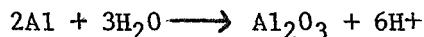
- (a) Wire surface ( $H_2O$  or hydrocarbons)
- (b) Plate surface ( $H_2O$  or hydrocarbons)
- (c) Moisture and/or hydrogen in shielding gases
- (d) Poor shielding and moisture from air
- (e) Interior of plate and/or wire.

For the purpose of this discussion, it will be assumed that everything has been corrected but (e). Also, hydrogen is considered as one of the elements in the composition of plate and welding wire. Evidence that links weld-joint porosity with the internal hydrogen content of plate and welding wire will be reviewed.

The other common defects of weld metal and heat-affected zones are cracks. International literature on aluminum casting and aluminum welding contains great volumes of information that associates cracking problems to alloy compositions. There is much confusion in these reports, but also many very good cause-and-effect relationships. While this subject is very large, a review of some of the major aspects is made.

## POROSITY

Heats of alloy aluminum for plate production are melted in various types of furnaces, many of which are the reverberatory type and use hydrocarbon fuels. There are several sources of hydrogen which can become dissolved in the metal during this operation. The major source of hydrogen is the reaction of water vapor with molten aluminum which produces nascent hydrogen.



Moisture is available from several sources:

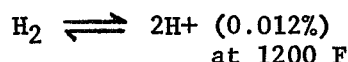
- (1) It is an end product of the combustion of hydrocarbon fuels, hydrocarbons + air  $\longrightarrow H_2O + CO + CO_2 + \text{other gases.}$
- (2) Moisture also enters this reaction as water vapor in the air used in burning hydrocarbons.

- (3) The scrap, ingot, and master alloying additions of the charge contain some (and can contain great quantities) of H<sub>2</sub>O combined with aluminum oxide surface layers.

Other sources of hydrogen that may dissolve in the melt are:

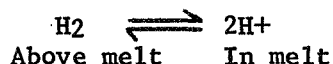
- (1) Hydrogen (atomic) in solid solution in the materials of the charge
- (2) Molecular hydrogen in blowholes and other voids in the charge materials
- (3) Breakdown of the fuels may produce some nascent or molecular hydrogen.

If molecular hydrogen is available over the melt at 1200 to 1400 F, about 0.012 percent of it can be ionized to nascent hydrogen and be in equilibrium with molecular hydrogen:



Nascent hydrogen from this source can dissolve rapidly and thus keep the reaction moving "to the right", producing more ionized hydrogen.

The rate at which hydrogen is dissolved in the melt depends on the composition of the alloy and the partial pressure of nascent hydrogen at the unprotected surface and time and temperature. A film of aluminum oxide over the surface can slow down solution of hydrogen greatly. It also can prevent escape of hydrogen. The presence of water vapor in contact with an unprotected melt surface produces a very high partial pressure of nascent hydrogen and thus the melt becomes saturated very fast. Magnesium in an alloy further increases the hydrogen content because of its reaction with H<sub>2</sub>O. When the melt is saturated at a given temperature the molecular hydrogen above the melt and the atomic hydrogen in the melt are in equilibrium as follows:



The amounts of hydrogen in solution in the saturated molten aluminum at various temperatures is shown by Figure 1. At the normal temperature of the melt, for example 700 C, there can be, and often is, 1 cc of H<sub>2</sub> per 100 grams of aluminum if the melt is saturated or in equilibrium with 1 atmosphere of hydrogen. If this amount of hydrogen were converted to bubbles at 1200 F, it would represent about 8 percent of the aluminum by volume. This is shown schematically to scale by Figure 2

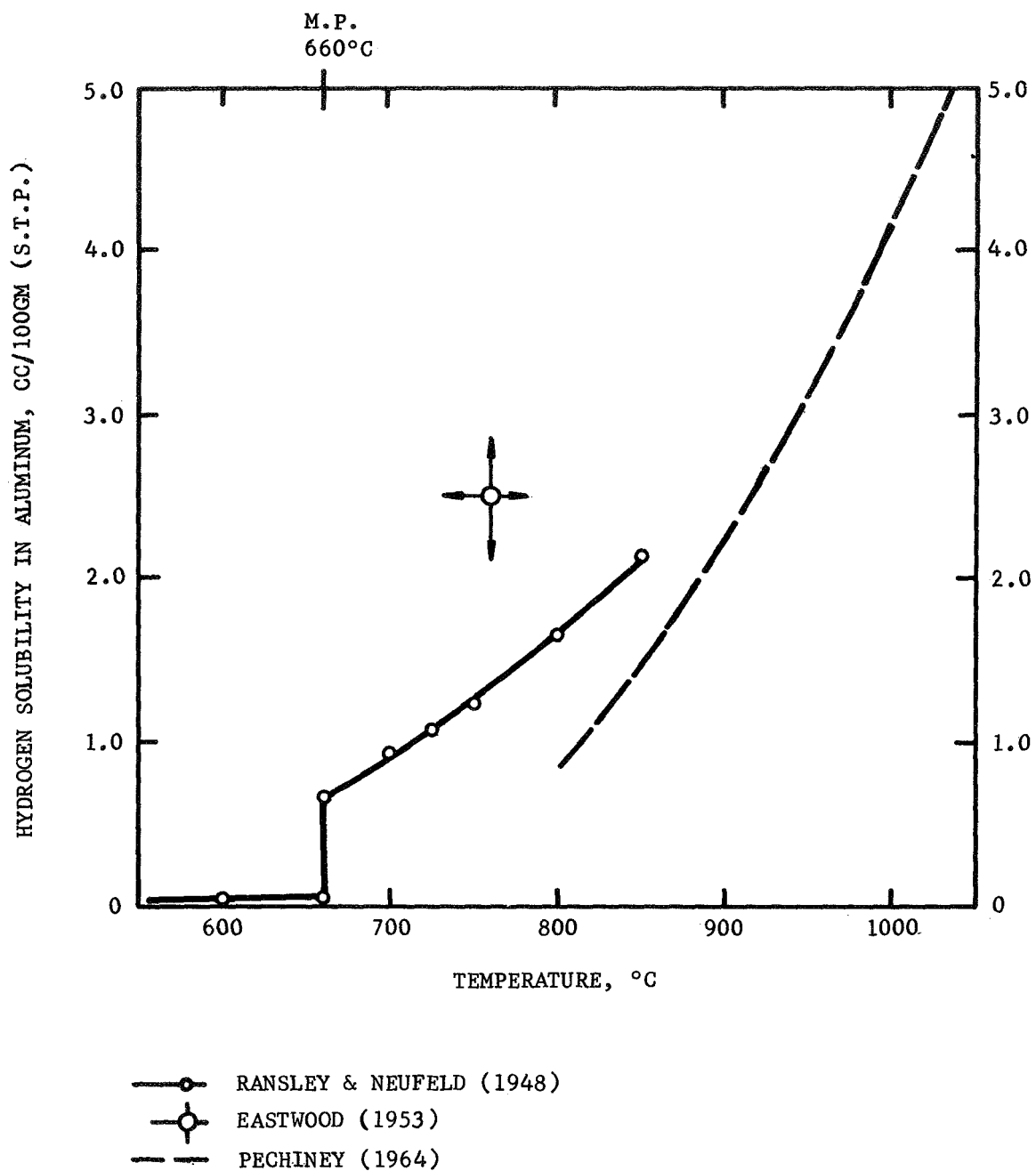
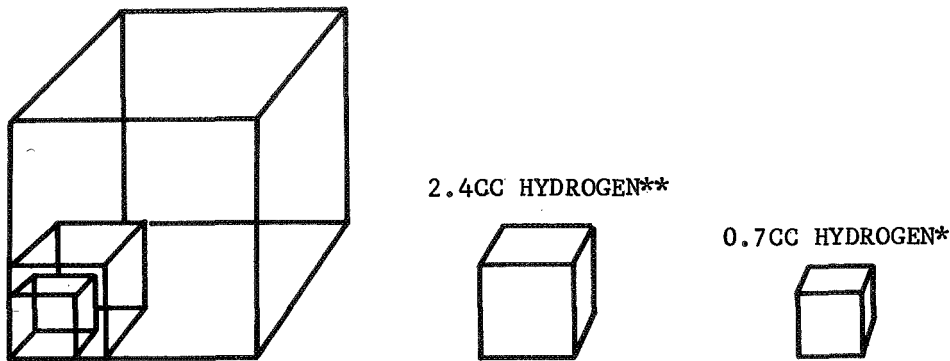


Figure 1. Solubility of Hydrogen in Aluminum

37CC (100 GM) ALUMINUM (600°C)



\*VOLUME OF HYDROGEN (S.T.P.) SOLUBLE IN 100 GRAMS OF LIQUID ALUMINUM AT 660°C.

\*\*VOLUME OF HYDROGEN (0.7CC AT S.T.P.) AVAILABLE FOR BUBBLE FORMATION AT 660°C.

Figure 2. Relation of Potential Volume of Hydrogen to Volume of Aluminum From Which it Can Precipitate During Freezing at 660°C.

Referring again to Figure 1, when aluminum and its alloys solidify, the solubility for hydrogen decreases very much. The solid metal has less than 1/10 the solubility of the melt. As the melt cools it rapidly becomes supersaturated and bubbles of hydrogen are evolved. Many may reach the surface and leave the metal. Others are trapped as blowholes, pinholes, or irregular grain-boundary cavities. The solid aluminum may end up by being supersaturated with hydrogen in the solid condition if cooling is sufficiently rapid.

In practice, considerable effort is made to remove the hydrogen from the melt before pouring ingots. This has to be done in order to obtain reasonably sound ingots. In this operation, the melt goes through a degassing step to remove dissolved hydrogen and a filtering step to remove dross and other foreign particles. Practice varies but usually includes these steps before going into the rapid-quench ingot process. Usually the molten metal in the ingot mold is not protected from the air and its moisture content.

The most important parts of this operation, for this discussion, are the degassing and pouring steps. The hydrogen can be removed from molten aluminum which has a clean surface by sweeping a pure dry gas such as argon over the surface and preventing moist air or any source of hydrogen from contacting it. This keeps the partial pressure of hydrogen above the melt very low and atomic hydrogen will diffuse out and be swept

away as molecular  $H_2$ . If this type of sweeping action is used or an area above the melt is evacuated, eventually all dissolved hydrogen could be removed from the melt. This would take a very long time because the surface is usually very small compared with the volume of the melt. In practice the process is speeded up by creating much more surface in the form of bubbles in the molten metal. Bubbles are usually made by flushing the melt with pure dry chlorine (See Figure 3.). There are many variations to this practice. Again, if (1) the hydrogen at the surface of the melt is swept away with dry gas containing no nascent hydrogen, and (2) the flushing is continued long enough, essentially all hydrogen will be removed from the melt. In commercial practice, the removal of all gas has not been accomplished consistently because there have been no quick and accurate tests that will tell the operator that all of the gas is out. Current literature, however, describes tests that may be put in practice in the future.

When the melt has been degassed to a low level it is difficult to keep it at this low level during pouring of the ingot. Pouring practices again vary with producers, but for the most part the metal is not protected from the air (and its moisture) except by the  $Al_2O_3$  surface layer during this short trip into the ingot chill mold and while it is freezing there. The alloy can pick up hydrogen very rapidly during this operation from water vapor in the air. The pouring techniques are designed to keep the gas pickup as small as possible but there is a good chance that some is always picked up.

For the purpose of this discussion: (1) it is assumed that a low level of gas is not always reached in the degassing process, and (2) some hydrogen is picked up during pouring. It is not unreasonable to assume that frequently during freezing in the ingot mold supersaturation occurs and blowholes, pinholes, or grain-boundary holes are produced in some part of this ingot. The frozen metal may be supersaturated in the solid state. This is shown schematically in Figure 4.

The hydrogen content of that ingot is not the amount shown for the solid solubility in Figure 1. The total content is the atomic hydrogen in solid solution plus the molecular hydrogen in the holes. The total can be very much higher than Figure 1 shows. Also it probably is not distributed uniformly in the ingot.

When an ingot containing hydrogen, as explained above, is processed into plate or sheet the hydrogen goes along and ends up in the final product. The blowholes, pinholes, and grain-boundary porosity get flattened out and welded together except for very small areas which contain the gas under pressure. This is shown schematically by Figure 5.

In the course of processing the ingot to plate the molecular hydrogen in the porosity may be increased. Additional atomic hydrogen may migrate to the holes from supersaturated solid material where it converts to molecular hydrogen and again sets up a  $H_2 \rightleftharpoons 2H$  equilibrium depending on the temperature and pressure.

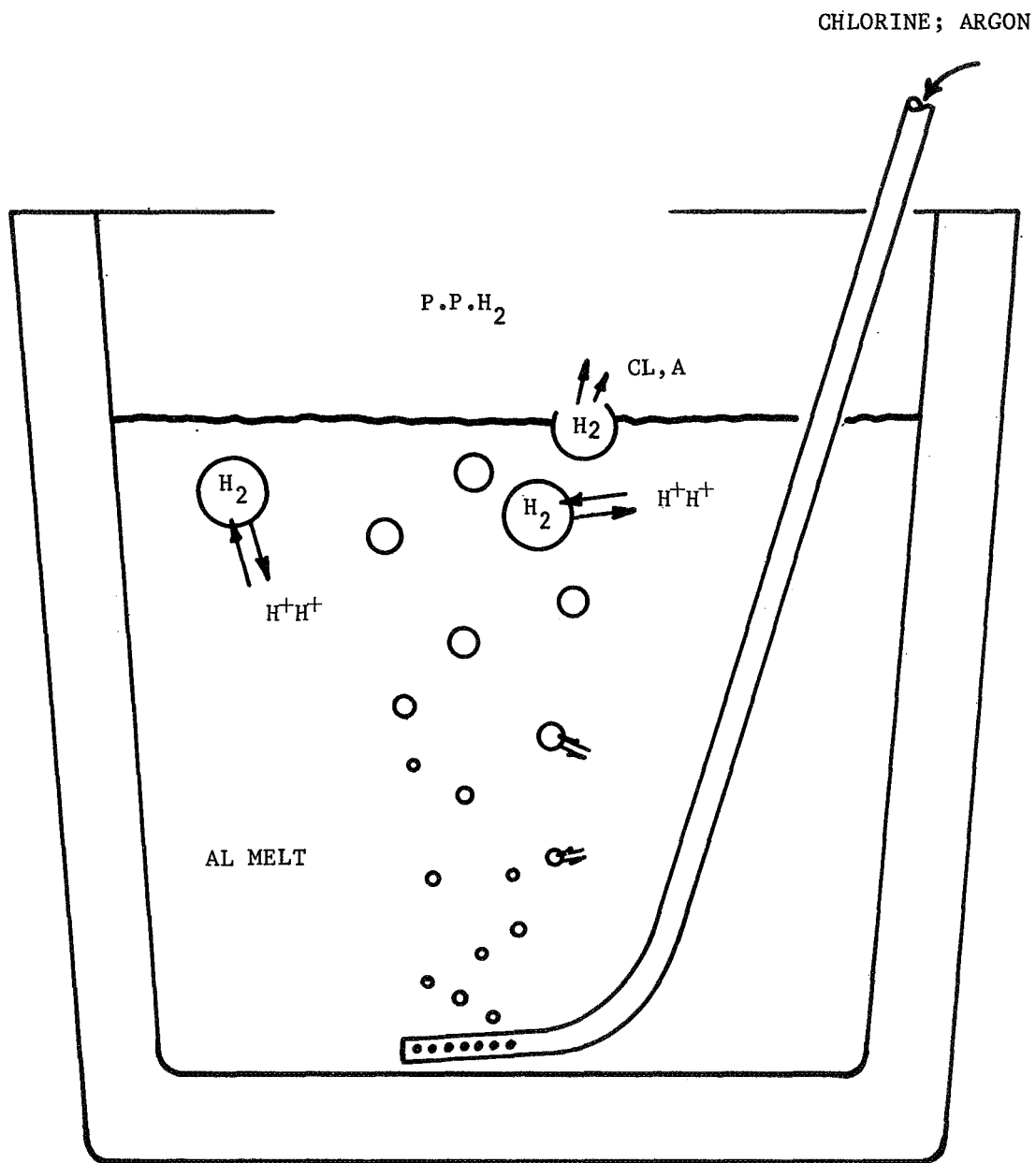


Figure 3. Schematic Sketch Showing Molten Aluminum Being Degassed

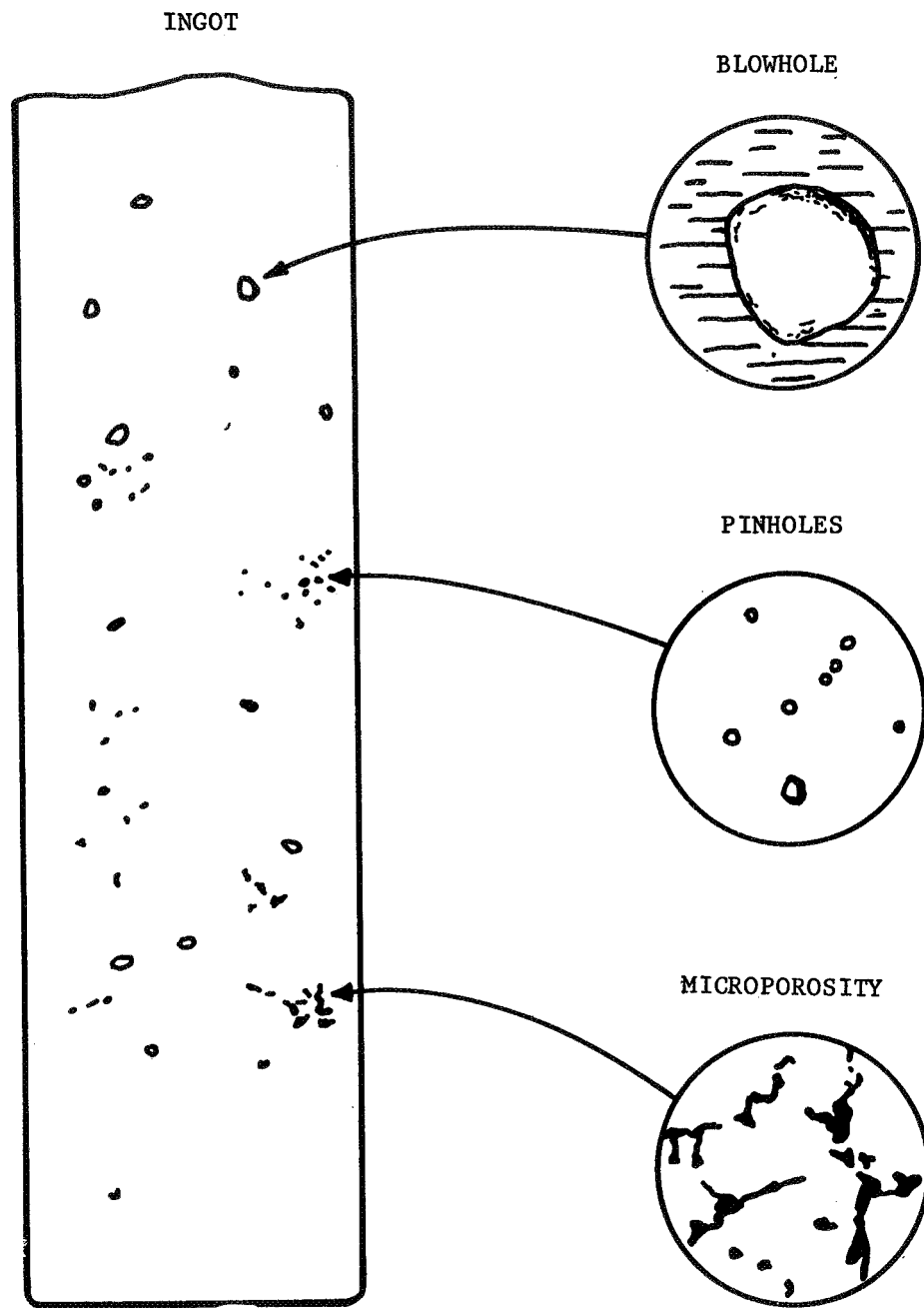


Figure 4. Schematic Sketch Showing Blowholes, Pinholes, and Microporosity in an Aluminum-Alloy Ingot



CROSS-SECTION OF AL PLATE OR SHEET ( OR WIRE)

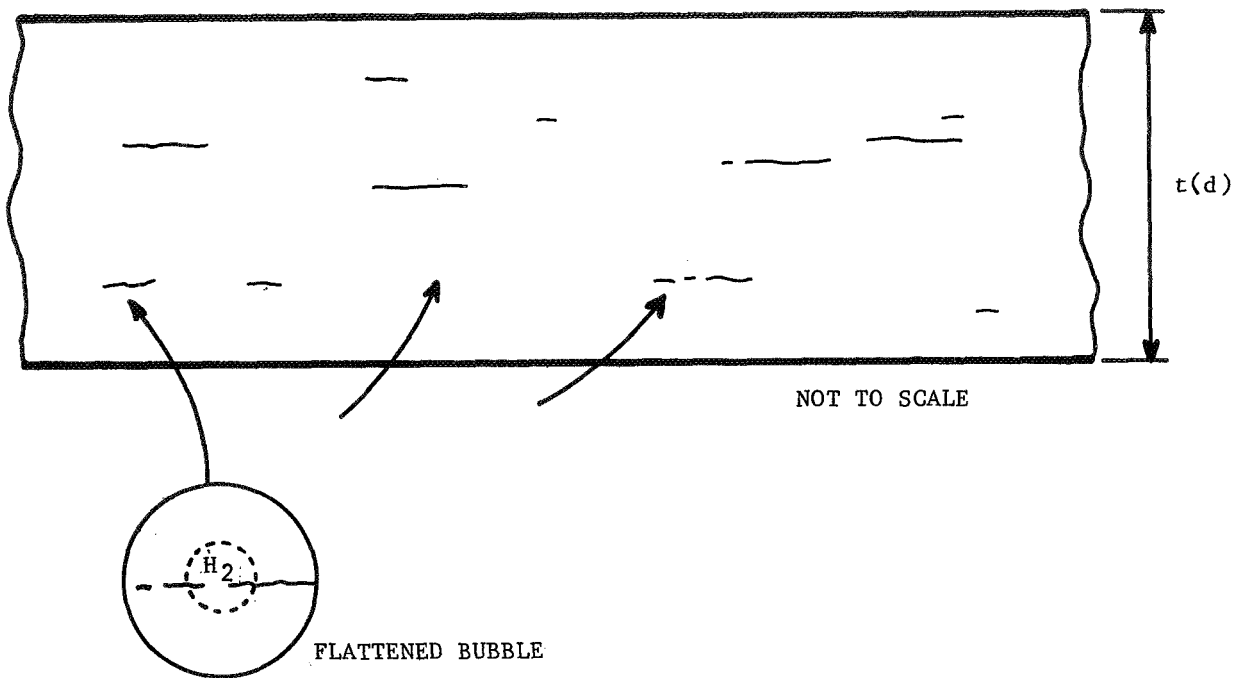


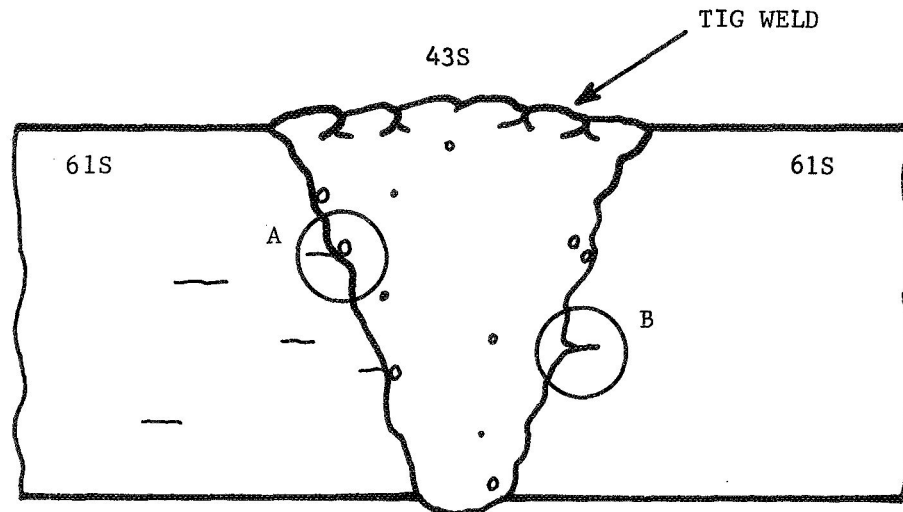
Figure 5. Schematic Sketch Showing Molecular Hydrogen Occluded in Plate

If an ingot is processed into welding wire the porosity likewise gets forced together, and for the most part, pressure welded, but the hydrogen will still remain in some parts of the now greatly elongated gas hole.

The small pockets of hydrogen under pressure in the plate or wire will be scattered in a pattern similar to their original distribution in the ingot. Some parts of the plate or wire have none, others may have several.

When plate with the above history finally reaches the welding shop or brazing shop as part of a structure, some interesting things can happen. One or many of the flattened holes in the plate may end up in a position like that shown in Figure 6.

If in the course of welding an area a pocket of gas is penetrated by the weld, one thing is quite certain to happen. A bubble will form. Depending on a lot of factors, this bubble may rise out of the weld pool and disappear. It was probably under pressure at ambient temperature in



A - TYPICAL HYDROGEN BUBBLE IN WELD METAL, ADJACENT TO LAMINATION IN BASE PLATE.

B - LAMINATION IN BASE PLATE WHICH OPENED TO ADMIT MOLTEN WELD METAL.

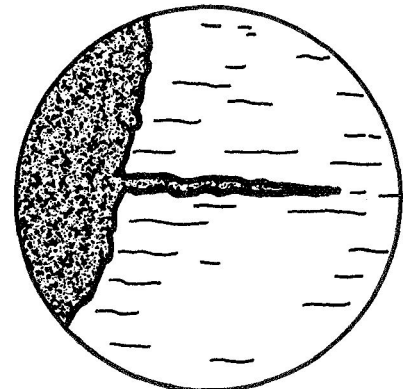
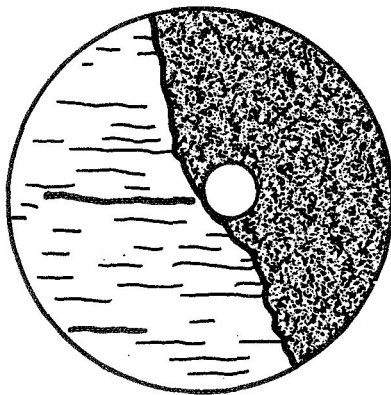


Figure 6. Schematic Sketch Showing How Occluded Molecular Hydrogen May Form Porosity

the plate. At 1200 F under 1 atmosphere of pressure it could become many times the size of its volume in the plate. It may get out during welding or it may be frozen in the weld before anything but expansion takes place. In the latter case it will show up in someone's radiograph and may cause rejection of the weld.

Such a pocket of gas may rise in the weld pool directly under the arc. In that case it may ionized to atomic hydrogen and go into solution again in the hottest part of the weld. It may or may not precipitate a bubble in cooler regions of the weld pool. If it does it may escape or be frozen in.

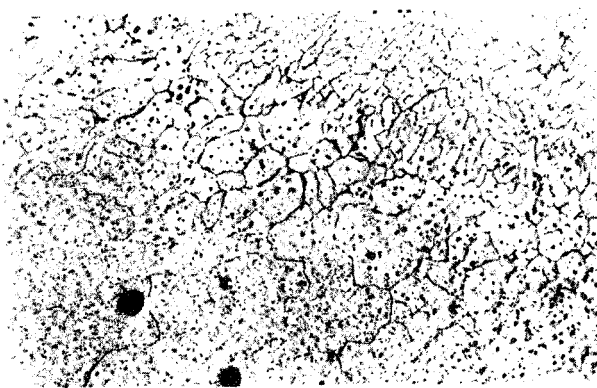
As a matter of interest it might be worth while to mention that the weld pool of the inert-gas-shielded weld has ideal conditions for both (1) degassing the liquid aluminum if the shielding gas is pure and dry, or (2) charging hydrogen in, if somehow moist air or other hydrogen-bearing gases are mixed with the shield. In both cases, except when direct-current straight-polarity TIG welding is used, the surface of the weld is kept very clean by the inert-gas protection and the positive ion bombardment cleaning action of the arc.

A clean surface swept by high-purity dry inert gas is an ideal situation to remove hydrogen, especially in MIG welding when fine droplets are passing across the arc. Time, however, probably prevents much of anything from happening.

The same very clean liquid surface swept by a gas containing some entrained moist air, or hydrogen from some other source, is ideal for charging hydrogen into the liquid metal. That is why a very efficient shield against air is necessary.

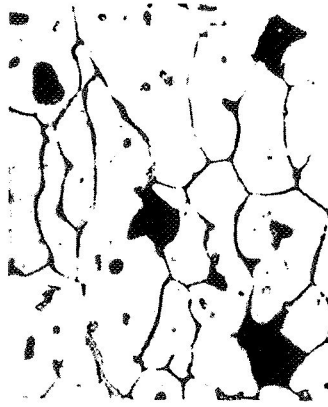
It has been reported by some welders that a very small amount of oxygen added to the gas shielding of direct-current straight-polarity welding helps prevent porosity. Since this type of arc does not have the cleaning action that removes oxides on the surface, a thin layer of oxide may form over the back part of the weld pool. This could help prevent hydrogen from being charged into the weld metal if some should be entrained in the shielding gas.

Returning again to Figure 6, another type of porosity is possible from the gas in the plate. This type can occur in the heat-affected zones of welds. The gas in the plate expands in the high-temperature area of the heat-affected zone and can form nearly round holes or more likely angular holes. This type of porosity has been observed and some samples are shown in Figures 7 and 8.



80X

Figure 7. Porosity in Heat-Affected Zone of Aluminum Weld (Westendrop)



300X

Figure 8. Angular-Type Porosity in Heat-Affected Zone of 2024 Aluminum Alloy (Koziarski)

Occluded gas in plate can produce another problem similar to that in the heat-affected zones of welds. This occurs in brazing operations. When aluminum reaches a normal brazing temperature it is within 50 to 100° F of the melting temperature and has almost no strength. The gas occluded in the holes can expand and produce blisters as shown by the braze sample in Figure 9.

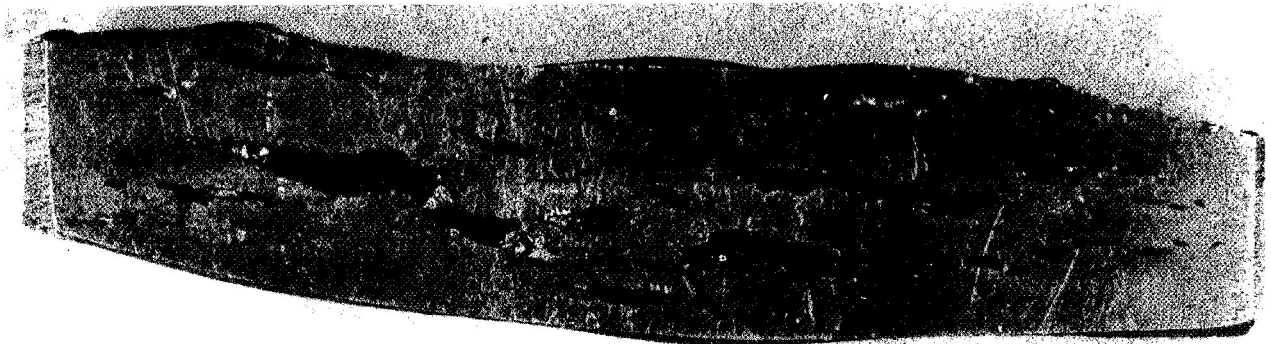


Figure 9. Blisters in Aluminum Sample after Brazing Operation

Those who produce high-quality wire for aluminum structural welding also have problems with occluded gas from the original ingots. One author recently described the need to have apparatus which inspects the wire for such defects by eddy-current methods and automatically cuts out the sections which show defects. If wire containing internal hydrogen is melted in the arc of the TIG welding process, the hydrogen may, or may not, end up in the weld. If it is released in the hottest part of the weld pool it will probably be dissolved and may, or may not cause porosity. If it is in wire used for MIG welding, it will be released in the hottest part of the arc. It will probably be dissolved but may, or may not, cause porosity.

A most interesting article on porosity in aluminum welds found in a recent literature search was one in which the authors reported adding 1 cubic foot per hour of dry chlorine gas through the contact tube of a MIG gun. They claim that this eliminated porosity under conditions that normally produce porosity. The mechanism is not explained but further pursuit of this idea might be worth while - in spite of possible toxicity and corrosion problems presented by chlorine in the atmosphere.

As stated earlier, the "phantom" cause of porosity is still with us. Little basic progress has been made since 1946 in eliminating this curse. There is ample evidence that the total internal hydrogen content of base plate and wire may sometimes be the "phantom" who strikes even when all guards are posted. Future precision control of hydrogen in the base plate and wire may be an important step toward final elimination of the problem.

### CRACKING

There is a great volume of information in the international literature dating back into the 1930 period on cracking of aluminum-alloy castings and welds. Only a few papers on the subject are to be found in the welding literature of the United States. A great bulk of the basic information has been published by the British.

Cracking in fusion-welded joints in aluminum alloys is directly related to the composition of the alloy. This is similar to cracking in any other group of alloys. There is always a fundamental link back to composition, just as any other property of an alloy can be related to composition. Some compositions are very crack sensitive and others are only slightly crack sensitive under a given set of conditions. Some alloys are so crack sensitive that it is not possible to weld them under normal conditions and are, therefore, not used for welded construction. The crack sensitivity of an alloy, as measured by a given set of conditions can be increased or decreased by changing conditions. Some factors which have a direct influence on cracking are welding processes, preheat, cooling rate, weld travel speed, weld size, gas content, condition of plate before welding, grain size, etc.

Weld cracking has been classified into two broad classes as follows:

- (1) Cracking above solidus
- (2) Cracking below solidus

The predominant type is the cracking above solidus (or hot cracking) which is intergranular in nature. It may occur in the weld metal or in the heat-affected zone separately or together. Below-solidus cracks may be intergranular in nature but in some instances are reported to be transgranular. This type of cracking occurs in weld metals and in heat-affected zones. Alloys susceptible to cracking at temperatures above the solidus may not be susceptible to cracking below the solidus, and the converse also may be true. Cracking may occur at temperatures both above and below the solidus in the same alloy, and fine cracks formed at temperatures above the solidus may, because of their stress-rising effect, initiate cracking at temperatures below the solidus when the cooling contraction of the metal is restrained.

Cracking in weld metal and heat-affected zones is believed by some to occur with the sudden dissolution of gas at, or near, the freezing point of the alloy.

As soon as an alloying element is added to aluminum such as copper, magnesium, or zinc the temperature range from the start of solid formation down to the point when the alloy is completely solid (or the liquid-solid range) is lengthened. When an alloy cools through the liquid-solidus range a series of things happen. It may cool under equilibrium conditions, that is, the composition of the solid phase and liquid phase are in equilibrium. On the other hand, as in a weld or a casting, freezing nearly always progresses too fast for solid-liquid equilibrium conditions to exist. In these cases, alloying elements continue to concentrate in the liquid phase which in turn extends the liquid-solidus temperature range and final freezing may not occur until the liquid phase becomes an eutectic.

In this freezing process, the first nuclei of grains appear at the highest temperature in the liquid-solidus range. The nuclei of grains develop into dendrites as cooling and solidification progresses. These dendrites progressively develop branches which eventually interlock with branches of other dendrites. Liquid phase collects and may be trapped between the dendrite branches. These pockets of liquid may be cut off from other liquid, and as the dendrites continue to cool and shrink there may not be enough liquid to fill the space, and separations called "hot tears" or "hot cracks" develop.

If alloys are cooled under equilibrium conditions, the ones having the greatest freezing range or liquid-solidus temperature exhibited the greatest tendency to hot crack. This is because the dendrites have more time to grow and thus shrinkage dimensions reach a maximum.

As stated previously, equilibrium conditions almost never exist during cooling of a weld or casting. Also, if cooling is fast enough, the final solidification may take place at eutectic temperature where the liquid phase reaches the eutectic composition. This liquid eutectic phase may serve a useful purpose by filling the shrinkage spaces that otherwise might be produced between dendrites. In other words it "heals" potential crack areas. Eutectic composition is found frequently between dendrites of welds and castings.

According to several authors the eutectic phase is often necessary (not always) to prevent hot cracking. There can be too little of it but seldom too much to prevent cracking.

Many investigations have been reported, especially by the British, on the above solidus cracking characteristics of binary, ternary, quaternary, and more complex alloys in ring castings and restrained weld tests. Commercially pure aluminum can be welded or cast without cracking. When small alloy additions are added the freezing range is increased and cracking increases. As more of an element such as silicon, copper, or magnesium is added the cracking reaches a maximum for a given set of conditions and then decreases again to a relatively low level. Figures 10a and 10b show the results of the addition of silicon to pure aluminum upon the crack sensitivity of small test castings and restrained welds. Similar data are available for binary alloys formed with nearly all of the major alloying elements used with aluminum. Some authorities have found that 23 percent by volume of eutectic is needed to prevent cracking in Al-Si, Al-Cu, and Al-Mg alloys.

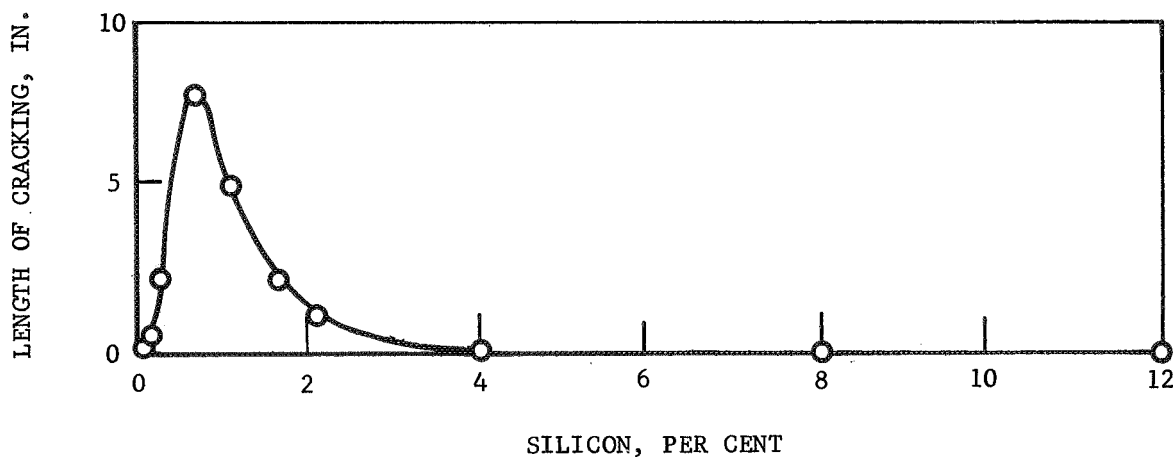


Figure 10a. Cracking of Ring Castings in Aluminum-Silicon Alloys of Commercial Purity (Singer and Jennings)

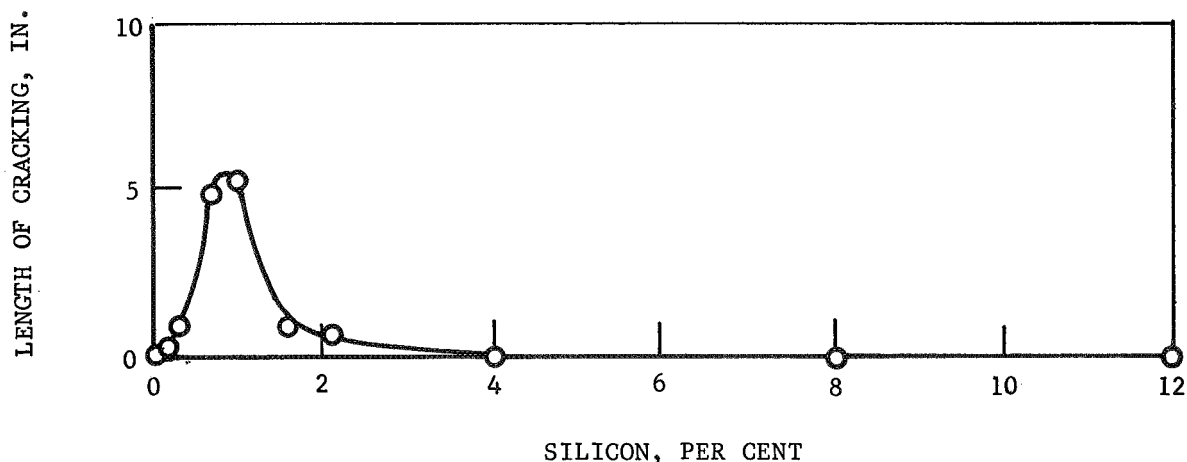


Figure 10b. Cracking of Restrained Welds in Aluminum-Silicon Alloys of Commercial Purity (Singer and Jennings)

The cracking tendency, as determined by a restrained weld test, of ternary alloys of aluminum-copper-silicon is shown by Figure 11. In this system maximum cracking occurs when the 1 percent copper and 1 percent silicon are added - the minimum when the alloy contains 9 percent copper and 3 percent silicon. The cracking tendencies of a series of complex aluminum-zinc-magnesium-copper alloys are shown by Figure 12. In these alloys, cracking increases and then decreases as the percentage of copper and zinc are increased together. A similar result can be seen as zinc and magnesium are increased together. Another diagram shown in Figure 13 shows cracking characteristics for a quaternary alloy.

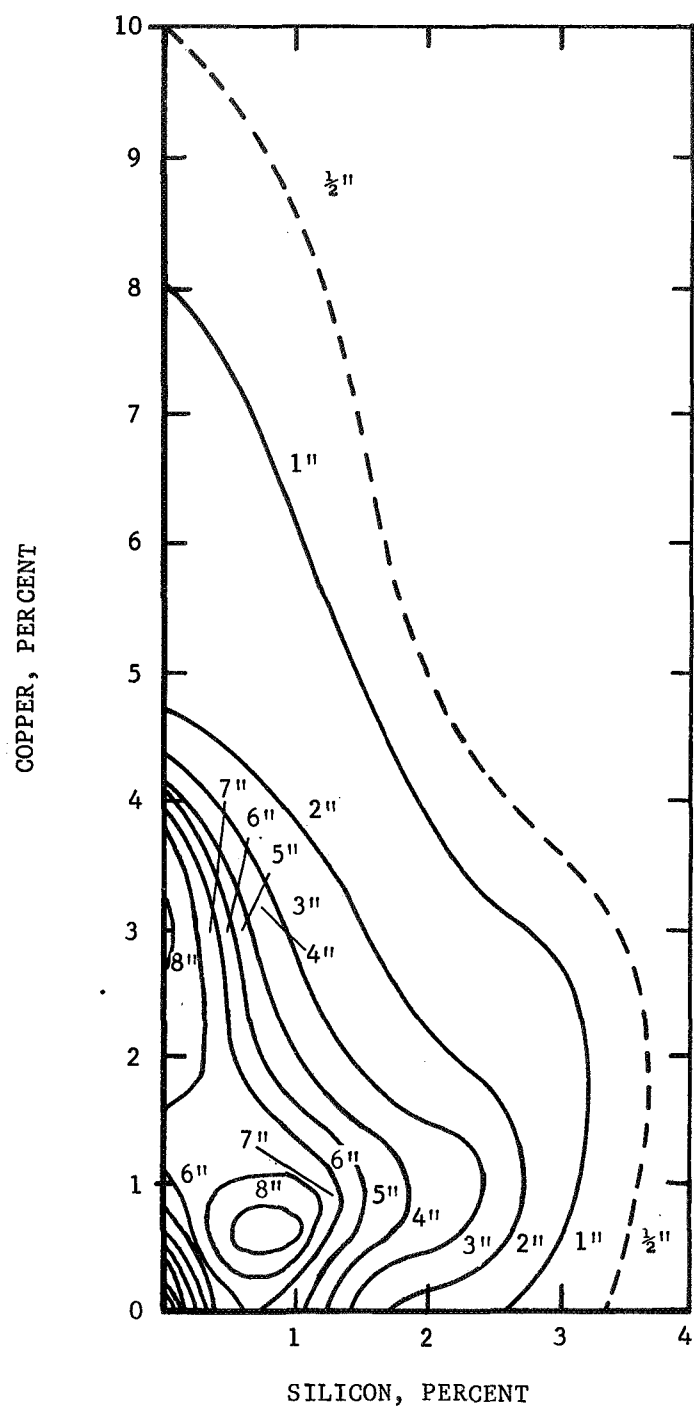
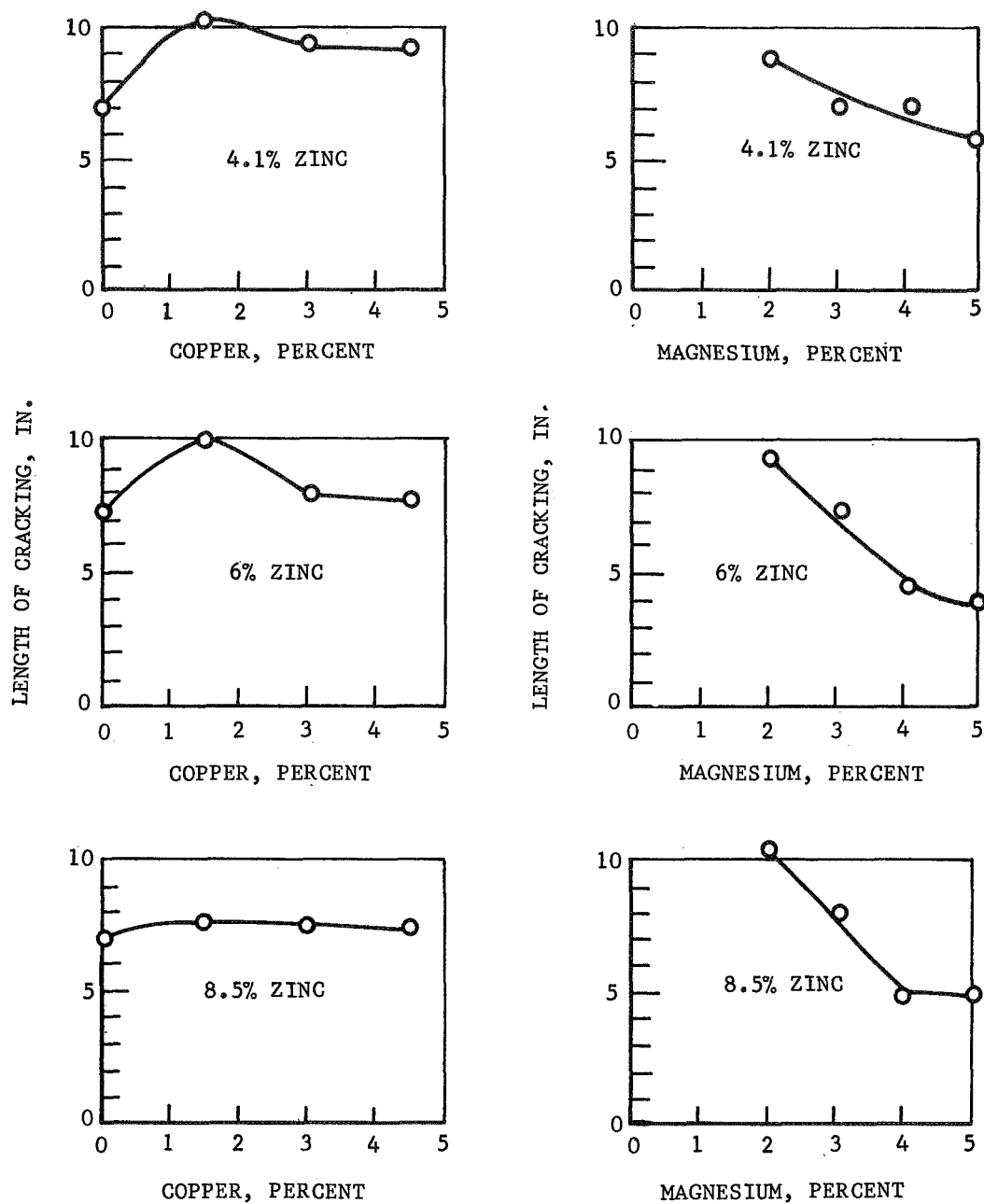


Figure 11. The Cracking of Restrained Welds in Aluminum-Copper-Silicon Alloys (Jennings, Singer, and Pumphrey)





ALLOYS BASED ON FIRST BASIC ALLOY(1)

ALLOYS BASED ON SECOND BASIC ALLOY(2)

Figure 12. Cracking Diagrams for Aluminum-Zinc-Magnesium-Copper Alloys (Pumphrey)

(1) 2.93% MG, 0.46% MN, 0.12% SI, AND 0.23% FE.

(2) 0.10% W, 0.10% MN, 0.25% CR, 0.12% SI, AND 0.22% FE.

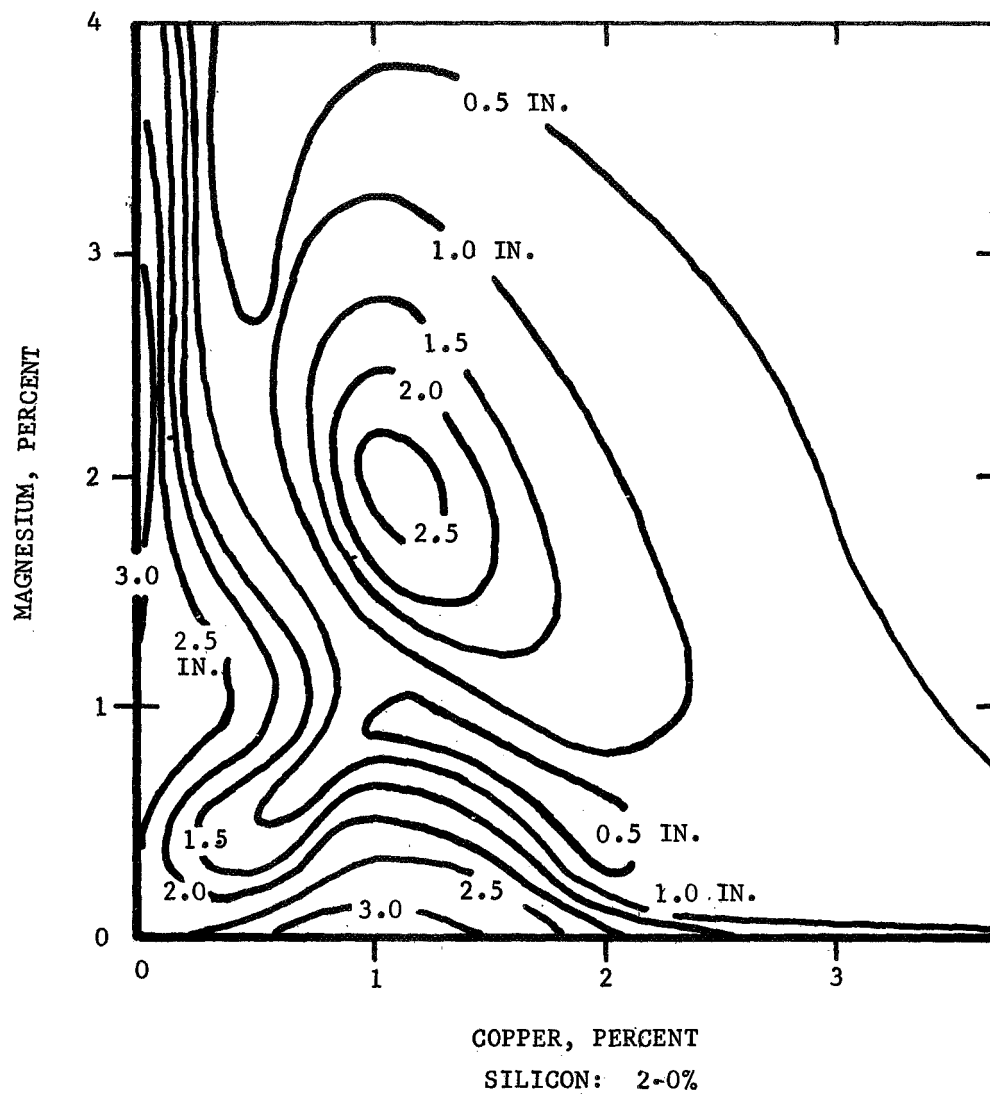


Figure 13. The Cracking Characteristics of Quaternary Alloys of Aluminum-Magnesium-Copper-Zinc (Pumphrey)

As stated previously, British researchers have reported many alloy studies made with ring castings, various types of restrained weld tests and oxyhydrogen, oxyacetylene, and TIG welding processes. Information from these experiments have had an important role in development of weldable alloys. Some contradictions (or exceptions) develop when various sets of data are compared because test conditions vary widely. Some agreements exist, however, and some conclusions have been made as follows:

- (1) A base metal of a given alloy series should be welded with a filler metal of the same series but of a higher alloy content.
- (2) Additions of grain-refining elements such as titanium, boron, zirconium, and vanadium reduce hot cracking.
- (3) The silicon content of Al-Mn alloys should be a little less than the iron content.
- (4) Impurities such as arsenic and calcium increase cracking.
- (5) Alloys that weld satisfactorily with the TIG process may not perform the same with oxyhydrogen or another process.

The first and second of these conclusions made several years ago are used widely today. For example, 2219 is welded with 2319 and 2014 is welded with 2014.

Cracking below the solidus has been observed in welds of alloys in the system of aluminum-copper-magnesium, aluminum-copper-magnesium-silicon, and aluminum-zinc-magnesium. This type of cracking has been related to inter-metallic compounds which have low ductility or are brittle. When these compounds occur in the grain boundaries, then the alloy may crack under conditions of severe restraint at temperatures in the range of 100 to 200 C.

In many cases small multidirectional cracks called "crazing" have been observed. These cracks have been found in the root weld and sometimes extend to the heat-affected zone. It has been suggested that "crazing" may be connected with porosity and may be produced by the escaping gas, which forces aside the thin film of liquid between grain boundaries and lifts up the grains. This may occur just prior to, or at, solidus temperature.

During welding, a portion of the heat-affected zone close to the fusion line of the weld is heated to nearly the melting temperature. As the distance from the fusion zone increases the temperature reached during welding decreases. Within this zone temperatures are reached which can do some important things which follow:

- (1) Expand small pockets of molecular hydrogen which may be occluded in the base material and produce a crack.

- (2) Cause precipitation of intermetallic compounds into the grain boundary or overage the alloy. These intermetallic compounds may be lower melting than the grains and thus incipient melting can occur. Under stress these areas may crack. Depletion of grain peripheries of alloying elements under some conditions leave the grain boundaries and the body of the grains stronger than the peripheries. Under stress these areas sometimes crack.

Aluminum-magnesium alloys containing 4.5 percent magnesium are known to crack in the heat-affected zones. Large heat-affected zones and repeated rewelding on alloys such as 2014 and 2024 have frequently produced heat-affected-zone cracks. A common precaution against this type of cracking is to weld as rapidly as possible using minimum heat and avoid rewelding.

As stated previously, weld and heat-affected-zone cracking tendencies of aluminum alloys are directly related to alloy composition. Cracking, however, must be measured under a given set of conditions if comparisons are to be made. Changes in conditions have an important influence on increasing or decreasing cracking. A typical example of this type of influence is that of welding processes. This is illustrated by Figure 14 which shows a marked change in the amount of cracking in aluminum-copper binary alloys when welded with oxyacetylene and TIG processes. Figure 15 gives a generalized illustration of the effect that processes have on cracking in aluminum binary alloys. The MIG part of this illustration is represented by a broken line because data are not available to properly locate it. The general pattern remains the same. The maximum cracking occurs at lower and lower alloy contents as oxyacetylene, TIG, and MIG processes are used. The maximum temperatures reached by weld metal, the size of weld pool, the heat-affected zone all change with the three processes, and in some complex way change cracking results. This leads one to speculate where the cracking curves for the same alloys for electron beam and processes such as narrow-gap welding, Figure 16 might fall on this chart.

It has been demonstrated that a change in shielding gas only from 100 percent argon to 65 percent helium - 35 percent argon can change the cracking curves as shown in Figure 17. Discontinuous TIG welds show a greater tendency to crack than continuous welds in otherwise duplicate restrained weld tests, as shown in Figure 18.

There is much other evidence that illustrates how the amount of cracking for a given alloy or series of alloys can be changed with welding conditions. There is a definite lack of basic information in welding literature on the cracking characteristics of aluminum base plate and filler alloys when welding is done with MIG, electron beam, and other processes developed in recent years. More data of this type could be useful in guiding future alloy developments. Apparatus is also available in which the thermal cycles and stress conditions that obtain in almost any weld or heat-affected zone can be reproduced at will. Use of this type of equipment and simple specimens should provide further guides to base plate and filler-alloy development.

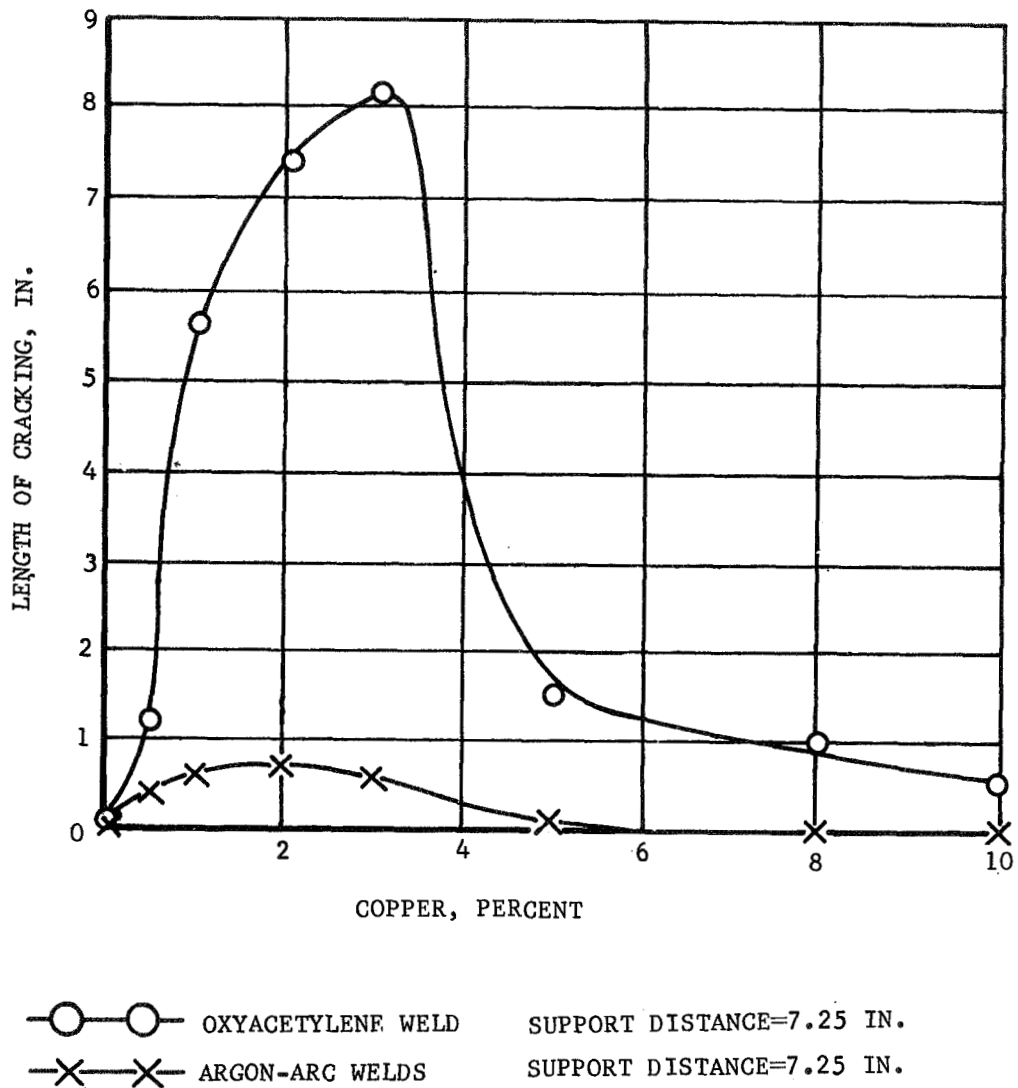


Figure 14. Cracking Curves for Aluminum-Copper Alloys (Pumphrey)

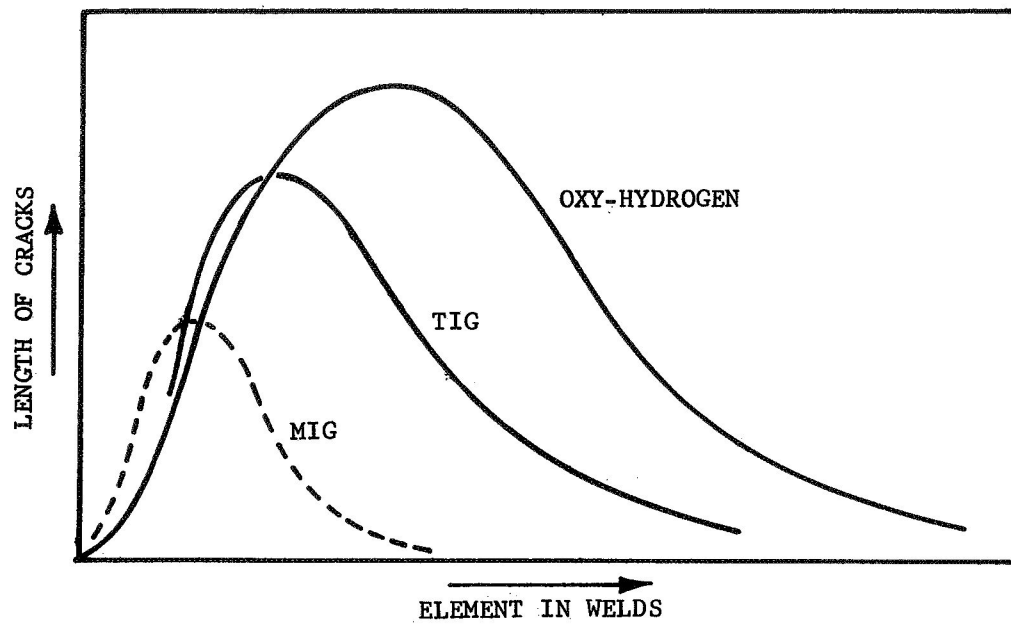


Figure 15. Effect of Welding Processes on Cracking (Young)

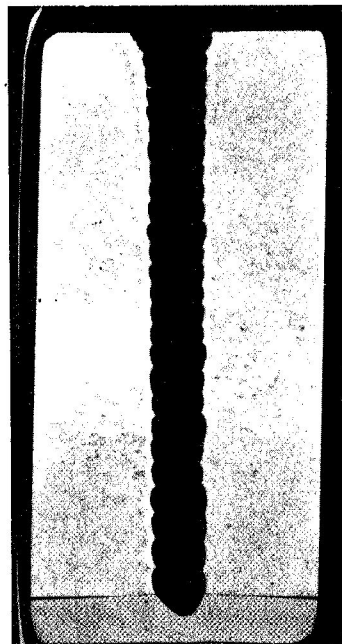


Figure 16. Narrow-Gap MIG Weld in 2219 Allow  
3 Inches Thick-2319 Filler Metal

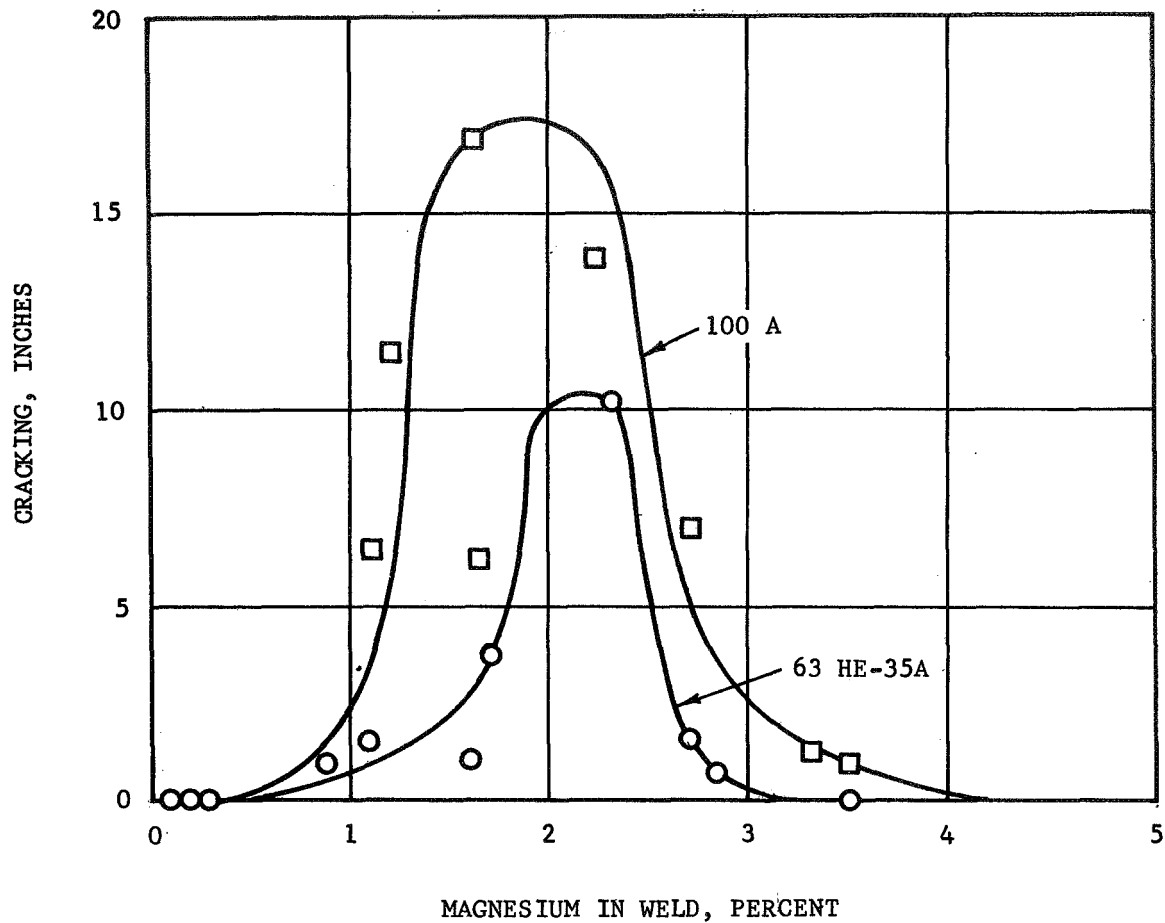


Figure 17. Weld Cracking of Aluminum-Magnesium Alloys in 100% A and 65% He-35% A (Dowd)

It is probably true that no aluminum-alloy composition will resist weld cracking under all welding conditions. Also, almost any alloy can be welded under certain restricted conditions. What can be hoped for are future alloys of high strength levels that have a high degree of resistance to cracking under normal welding conditions, and the other properties that make them useful.

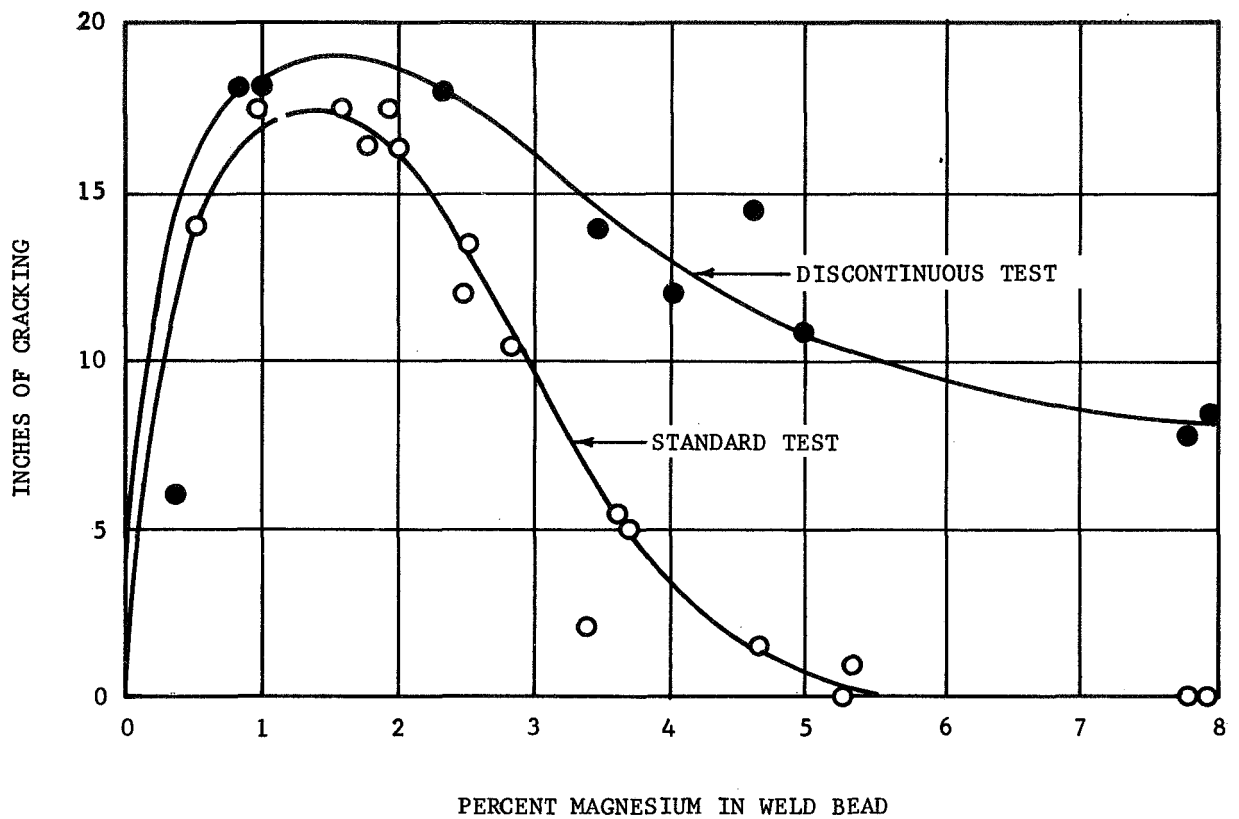


Figure 18. Effect of Magnesium Content of Weld Bead on Cracking of Welds in Aluminum-Magnesium Alloys (Dowd)



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## DISCUSSION

Mr. Gordon Parks: Perry, did you imply that perhaps we're lacking in our melt control? And is there any evidence to substantiate that other than what you have offered here?

Mr. Rieppel: Well, I think I'm implying, and I think I said this, that when it comes to degassing a melt, there have been no good methods right on the operator's basis to determine if you have the gas out or if you don't have it out. (There are some tests right now that look pretty good for that.) So, when the degassing is done, they're not certain whether they have it out adequately or not. Now, I don't say there are no controls, but I'm saying that you could on a production basis every now and then have a melt that is not degassed enough. And then, when you carry that over to the ingot, you can produce blow holes.

Mr. Parks: Now, the second question relates to the paper by Mr. Schwenk yesterday morning concerning electron beam welding. He indicated that porosity was a problem. Based on your concluding statements would that be a true indication that the gas is trapped in the base metal?

Mr. Rieppel: Not necessarily. You still have a surface. You still have a couple of surfaces that are involved. You know that if you clean a surface now, 10 minutes later it has some oxide and water on it. So, it's very difficult to know that you have a clean surface. If you're welding a joint together, you cleaned it at some time, whether it was in the electron beam unit or somewhere else. Now, the fact that it's in the vacuum would not necessarily remove the moisture that is on the surface, because it is combined with the oxide, and I don't think the vacuum would necessarily remove all of it. It could point to the question that if you had cleaned up everything and were sure it was clean, where else does the porosity come from? Sometimes we are mistaking porosity for perhaps little shrinkage cracks or little shrinkage holes. This is not too difficult to do when you get down on the micro size. You may mistake little shrinkage holes for porosity. However, if they are round, I would suspect there was some gas there.

Mr. Chyle: Is there another question?

Mr. Jim Williams: Perry, I have a question concerning the porosity that occurs in aluminum. Sometimes when we look at the fracture of our tensile specimens, we can note a residual on the surface of the pore itself. Have your studies included any analysis of the content of this residue which sometimes is a brown color, sometimes a black color, and the pore itself appears to be very bright? Have your studies included any review of these residuals, their content, and what may cause them?

Mr. Rieppel: We looked at a couple of samples of this kind just recently with the electron micro probe. The only thing we found---this was in 2219---was quite a bit of the aluminum-copper compound there. Now, I don't know if this would in any way account for that surface appearance. Otherwise, I can't say what this dirty color might be. At the temperature that the bubble was formed, you could not expect any vaporized metal. Now, when you see the smudge along the side of a weld, this for the most part is condensed metal that was vaporized, and

it will look something like the smudge you see on the inside of a hole. But, I don't know if it is the same or not. Nitrogen will sometimes give you a surface on a weld that is a little bit brown and dirty, but I would not expect nitrogen in this place either.

Mr. Cline: Perry, we ran some evaluations on the weld porosity and we found in almost all cases, and for Jim's benefit too, that inherent gas porosity is almost invariably clean. We also found the porosity is often caused by hydrocarbons that enter the weld puddle from the cold wire feed, in the case of TIG welding, and that these surface oxides in many cases can be a hydrocarbonous type of material. The entry of small particles of spooling or reeling material through the wire feed, or foreign substance can and often does contaminate the wire guide system.

Mr. Rieppel: I think that if you had hydrocarbons involved--of course you could have some of the products of breakdowns of hydrocarbons---they might deposit along with the bubble of hydrogen. This I think would be possible. As a rule, I agree that practically all the holes I have ever seen---the ones that you break open---are quite clean and quite shiny on the inside.

Question: Perry, one thing disturbs me in seeing some of your slides and listening to the talk. Normally, in the solidification of a metal, we have a solidifying front. In this case in welding, solidification is so rapid it would be a dendritic growth, which means we would have a main branch going out and side branches going off the main. Based on the curve shown by you and Hi, which shows the rapid drop in the hydrogen content, going from liquid to solid, you would expect the hydrogen or whatever gas that might arise to be rejected to the solidified front of the liquid. And yet, when we look at a lot of the metallography of welds, much of the porosity is in the dendrite itself. I find this hard to understand. It is disturbing.

Mr. Rieppel: I think that part of that may be due to the fact that it is cooling so rapidly. But there probably is a case that as the dendrites are formed, you are extruding, in effect, the liquid in between them, and this in most cases would be carrying most of the hydrogen you would expect to be deposited on the grain surfaces as they are being formed. But I can not answer your questions as to just why you would find them in a dendrite, unless this was again freezing fast enough that it just got trapped there. I can't explain why you might find one right in the dendrite.

Mr. Schwartzbart: Perry, another thing that bears on all this, of course, is the viscosity which goes up enormously around the solidus. The gas is trying to get out, and the thing that's keeping it in is the viscosity of the liquid material that it has to go through to get out.

Mr. Brown: Perry, I want to make a comment because it may be pertinent to the question you were asked by Stan a few minutes ago. You said that all the hydrogen could be taken out of the bath by passing a gas, inert gas of some type, over the surface. This not true. We found in aluminum particularly that one reason why we bubble gas through metal is because the hydrogen is many times associated with oxygen inside of a bubble, unless it's inside of a film. This film is finely divided and will float in the form of very minute particles of dross and will not come out under any normal passage of air on the surface, even if it's conditioned air. So you have to put something there

which in essence attacks that oxide film, breaks it down, and releases the hydrogen. The tenacity of this material may be the same thing mentioned here by the last gentleman as the reason why it's not moving with the front and solidifying where it is.

Mr. Rieppel: You're saying that a particle, some non-metallic, gets caught in a dendrite, and a bubble is forming around it. It has to have a nucleus to do this. Well, to me at least, I think this would make sense. But this matter of whether you get it out or don't get it out may be a mute question as to just how far you can go. But if you are going to run an analysis of the gas that's in aluminum, you use a vacuum. In the vacuum, all you do is remove the partial pressure of hydrogen, and if you keep the partial pressure down to zero, anything that's in there is going to come out except for just whatever little pressure there is from the head of aluminum which you may have. Essentially, nearly all of it will come out if you do that long enough. But as you say, you might trap a non-metallic. This might remain in your melt and a bubble will cling to it. This could happen.

Mr. Chyle: I wonder if someone from the aluminum Company, here, might want to make a few statements as to the presence of, say, residual hydrogen. Is there any statement that we could hear from them? Gus, do you wish to commit yourself a little bit, here?

Mr. Hogelund: Our problem is measuring and controlling it. As for the presence of hydrogen and remelting metal, we can start clear back from the reduction pot and storing of the ingot. You can get good quality metal; you can get bad quality metal. There are some other aspects to this thing though. There's nothing in here about the effect of porosity, although there has been considerable work done in steel and aluminum. It's a question of where you put your standards as to how much porosity is permissible. We have been talking about the metal and how much hydrogen it contains. A great deal of study of the metallurgy, the gas and so on is going on, and these things are pretty well understood in the aluminum industry. Now, how to get it less than this, at a reasonable cost, control it, and measure it is our problem. Perry made a very significant statement when he said, "Methods are coming about which will measure hydrogen." If we can measure the hydrogen, we can control it, and we'll do that. This has been true in the industry since it started to improve quality. And I think aircraft and perhaps now the space missile industries will apply the pressure to improve this quality. The effect on mechanical properties of oxide film entrapment, and a great many other things, I think is much more important. I don't propose to get into a discussion as to how much porosity effects the performance of a weld, but if you'll look at the standards for steel structures, the amount of porosity you fellows are talking about is very small. And we can get ourselves into a corner by attacking this stuff and going to great lengths to get rid of it. We'd better be sure we want to get rid of it and that it's necessary to get rid of it. But as far as improving the gas in the metal, the industry is in the forefront, I think, in both of these methods. We're certainly not arguing with this point of view at all.

Mr. Chyle: In the interest of time, we must close this paper and, again, we wish to thank Perry Rieppel for this very interesting talk.



POROSITY FORMATION AND SOLIDIFICATION PHENOMENA  
IN ALUMINUM WELDS

By

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## ABSTRACT

Previous work has clearly demonstrated that hydrogen is the greatest single cause of porosity in welds. It also indicated, in a qualitative way, that the final distribution of porosity in aluminum welds was determined by nucleation and growth kinetics. This work has been extended in an effort to obtain a quantitative description of porosity formation in terms of nucleation and growth rates.

Analysis of porosity formation was undertaken using thermodynamic and classical nucleation and growth rate theories. These theories, when modified to account for unique weldmetal solidification phenomenon, appear to be capable of describing the kinetics of porosity formation in aluminum welds.

## CREDIT

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## INTRODUCTION

The problem of porosity formation in aluminum-base alloy welds and castings has been the subject of numerous investigations (References 1 through 7). These and other studies have conclusively proved that hydrogen is the principal, if not the sole, cause of porosity. An excellent annotated bibliography (Reference 8) presents overwhelming evidence on this point. Although the role of hydrogen is well known, virtually nothing is known of the kinetics of porosity formation. An understanding of the kinetics is especially important in welding, where the range of heating and cooling cycles can exert important effects. A recent study (Reference 9) has demonstrated that porosity formation in fusion welds may be qualitatively described in terms of the nucleation and growth concepts of physical metallurgy.

The complete understanding and total solution of the aluminum weldmetal-porosity problem is dependent upon the eventual quantitative description of nucleation and growth rate phenomena. This paper describes an approach, whereby such fundamental data may be obtained. The methods of analysis employ novel adaptations of thermodynamic and classical nucleation and growth rate theories. Unique phenomena associated with the solidification of weldmetal play very important roles in the analytical approach.

A small number of specimens, remaining from a previous investigation, was used to gather preliminary porosity nucleation and growth rate data for analysis. The results of this analysis indicate that the theoretical approach is valid and should ultimately provide a more comprehensive understanding of the mechanisms of porosity formation in aluminum-base alloy welds.

## Background

A previous investigation (Reference 9) was performed in which the nature and causes of porosity in aluminum weld deposits were studied. The results showed that, for bead-on-plate, MIG-deposited welds in Type-3003 plate, moisture in the arc atmosphere was the most significant cause of porosity among the many factors studied. Porosity concentration increased sharply when the dew point of the shielding gas exceeded minus 40°F.

The dependence of porosity formation on welding thermal variables was investigated by depositing welds in moisture contaminated (dewpoint =  $-25 \pm 5^{\circ}\text{F}$ ) arc atmospheres. Figure 1 (Reference 9) depicts the dependence of porosity concentration on welding travel speed for a given set of conditions.

The welding conditions employed gave very little porosity at 10 ipm, gross porosity at 25 ipm, and moderate porosity at 40 ipm. Not only did the concentration of porosity exhibit a relative maximum, but the size of the individual pores tended to vary from fine at high travel speeds to coarse at lower travel speeds. The results strongly indicated that the final distribution and size of pores was governed by the time available for pore nucleation and growth during the time the weld deposit was solidifying.

A similar dependency is depicted in Figure 2 where porosity concentration is shown as a function of a cooling-rate parameter which is expressed in terms of several welding variables ( $s$  = arc travel speed, ipm;  $I$  = arc current, amperes;  $E$  = arc voltage, volts;  $T$  = plate thickness). The parameter was taken from an analytical expression derived by Adams (Reference 10). Figure 2 shows data for welds deposited in a 65 percent helium-35 percent argon atmosphere (dewpoint =  $-25 \pm 5^{\circ}\text{F}$ ). Additional data on welds made using moisture-contaminated argon or helium shielding exhibited generally lower porosity concentrations than those deposited with either argon or helium/argon shielding.

At low values of the parameter, or slow cooling rates, the porosity level was found to be low and the few pores present in the weld were large in size. For high values of the parameter, or more rapid cooling rates, the porosity concentration tended to be low, and the pores were generally fine. In between these two extremes the porosity level exhibited a maximum, exceeding 25 percent by volume. The pore sizes at the maximum level were generally rather large.

The dependency of porosity concentration (and size distribution) on the apparent cooling-rate may be qualitatively explained in terms of nucleation and growth (Reference 9). Once a stable pore is nucleated, its subsequent growth requires time for the inward diffusion of hydrogen or for coalescence with neighboring pores. Rapid cooling rates (high values of the cooling-rate parameter) would tend to retard growth since the time available for hydrogen diffusion and coalescence would be brief; hence, pore size will be small. As the cooling rate decreases, the time available for pore growth will increase and increased volumetric concentrations would be expected. For extremely slow cooling rates, sufficient time would be available for the eventual outgassing of the hydrogen contained within the pores. At some intermediate cooling rate, the time available for growth and coalescence would be of sufficient duration to permit the formation of substantial porosity concentrations.

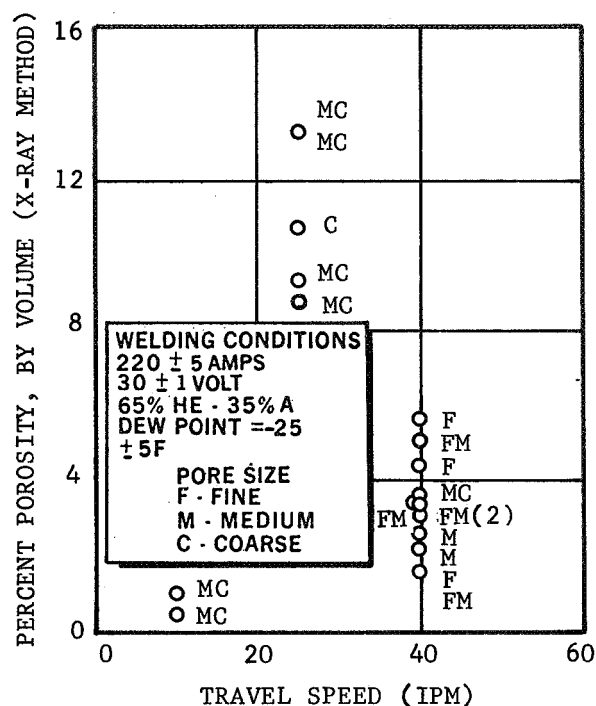


Figure 1. The Effect of Travel Speed on Porosity Formation

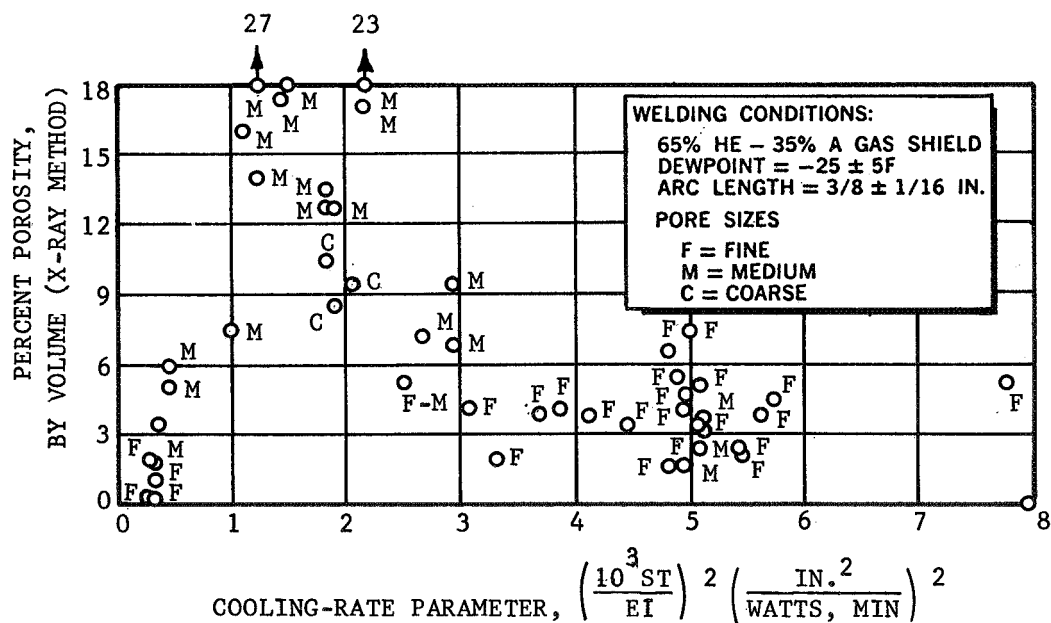
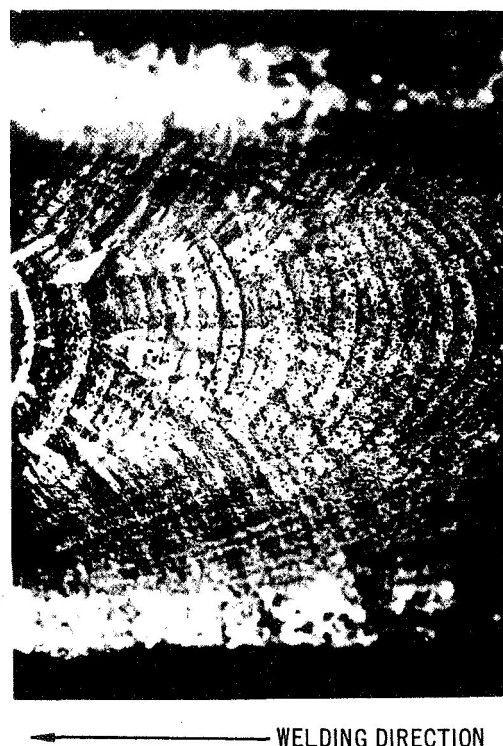


Figure 2. Porosity Versus Cooling-Rate Parameter-Helium/Argon Shielded Welds

Figure 3. Typical Ripples on the Surface of a Bead-On-Plate MIG-Deposited Weld in Type- 3003 Plate, Lightly Electropolished, 10X Magnification



In summation, previous work has demonstrated that nucleation and growth reactions may be used to qualitatively explain the experimental results relating to porosity formation in aluminum welds. The subsequent sections of this paper deal with a tentative quantitative analysis and its application to a small sample of porous weld deposits.

#### Weldmetal Solidification Phenomenon

Before proceeding with discussions of the theoretical analysis, Porosity consideration of the mode of weldmetal solidification is necessary. Many metallurgical reactions that occur within a weld deposit will be strongly influenced by the mode of solidification. Porosity formation, as will be discussed in subsequent sections, represents a metallurgical reaction that falls within this category.

The solidification of the fusion zone of a weld deposit is rather a unique phenomenon. Unlike castings, weld deposits freeze at least an order of magnitude faster than the most rapidly chilled casting. Furthermore, the thermal gradients associated with a linearly moving constant-velocity arc impose a rather unique heat-transfer condition. Extremely steep thermal gradients persist at the leading edge of the molten weld-puddle (Reference 11). Somewhat less severe gradients exist near the trailing edge of the molten weld puddle. As a result of these gradients, solidification of the weld-puddle occurs in discrete volumetric increments rather than as a continuous steady-state process more characteristic of a slowly solidifying casting.

The discrete increments (referred to, henceforth, as ripple-zone volumes) manifest themselves as the commonly observed ripples on solidified weld surfaces. Figure 3 illustrates typical ripples on the surface of a bead-on-plate fusion weld in 3003 aluminum alloy. The pattern is representative of that observed on the surfaces of most fusion welds.

The ripple-zone solidification time, and the corresponding ripple-zone volume, represent basic weld-deposit solidification-parameters. These parameters will be used extensively in the theoretical and experimental analysis of porosity nucleation and growth to be discussed in subsequent sections.

### Thermodynamic Nucleation and Growth Theory

Classical thermodynamics (Reference 12) may be used to demonstrate the factors affecting the two major parameters (gas nucleation and pore growth) and to show how these may be used to explain observed, experimental behavior.

#### Nucleation

A stable nucleus of formerly dissolved gas will form when the Gibbs free energy ( $\Delta F$ ) becomes negative. This quantity may be expressed as the sum of component free-energies:

#### Equation (1)

$$\Delta F = -\Delta F_m + \Delta F_s + \Delta F_c + \Delta F_e,$$

where  $\Delta F_m$  is the chemical free energy of the nucleating gas,  $\Delta F_s$  is its surface free energy,  $\Delta F_c$  is its strain energy, and  $\Delta F_e$  is the change in free energy resulting from the change in its internal pressure. Since this work is primarily concerned with gas evolution in the liquid state,

$\Delta F_c$  and  $\Delta F_e$  will be negligible. Under these conditions,  $\Delta F_s$  sets the lower limit on the size of the stable nucleus. If  $\Delta F_s$  is too large (molecular agglomeration too small), the nucleus will redissolve. If  $\Delta F_s$  is small (molecular agglomeration large), the nucleus will grow. Equation (1) may be rewritten as:

#### Equation (2)

$$\Delta F = -k_1 a^3 + k_2 a^2,$$

where  $k_1$  is the chemical energy per unit volume and  $k_2$  is the surface energy per unit area and  $a$  is the radius of the nucleating particle. The equilibrium nucleus size derived from equation (2) is found to be

#### Equation (3)

$$a_0 = \frac{2}{3} \frac{k_2}{k_1}$$

and the change in free energy thus becomes

Equation (4)

$$\Delta F = \frac{4}{27} \frac{k_2^3}{k_1^2}$$

The smallest stable nucleus that will form an observable void is that which forms just above the eutectic or solidus temperature and has sufficient time to grow. Under these conditions, the equilibrium nucleus size,  $a_0$  of equation (3), will be a constant, and equation (3) may be employed to re-express equation (4) as

Equation (5)

$$\Delta F = \text{Const. } k_2$$

Thus, the change in free energy will be an inverse function of the radius ( $r$ ) of the particle as given by

Equation (6)

$$\Delta F = \text{Const. } \frac{1}{r^2}$$

since the surface energy varies inversely as the area of the gas nucleus.

In the liquid state considered here, the diffusion of the gas atoms through the liquid to the growing nuclei will be relatively unimpeded (Reference 13). The nucleation rate,  $N$ , may be approximated by

Equation (7)

$$N = \text{Const. } \exp -\Delta F/RT$$

However, the solidification temperature of a given alloy is constant until solidification is completed, so that equation (7) may be rewritten using equation (6) and a series approximation for  $e^x$  as

Equation (8)

$$N = \frac{\text{Const.}}{r^2}$$

Pore Growth

Equation (8) provides an approximation of the rate of nucleation of the smallest observable gas bubbles which grow just above the liquidus temperature. The rate of growth,  $G$ , of these bubbles must now be described. The growth rate of a sphere is given by

Equation (9)

$$G = \frac{dV}{dt} = 4 \pi r^2 \frac{dr}{dt}$$

where  $V$  is the volume of the growing bubble and  $t$  is the time. At a given temperature, such as the eutectic temperature, the bubbles may be assured to grow at an essentially constant rate. Expressed mathematically,

Equation (10)

$$dr = \text{Const. } dt$$

Integration of this equation gives

Equation (11)

$$r = \text{Const. } (t - t_E),$$

where  $t_E$  is the time of growth at the eutectic temperature. For a given alloy which does not possess a thermal arrest of a eutectic nature,  $t_E = 0$  and  $t$  is taken as the total time for solidification (i.e., ripple-zone solidification time). For a given aluminum alloy composition subjected to a given amount of superheating, the solidus will be very nearly a constant value. Thus, all bubbles which grow larger than what was previously defined as the smallest observable bubble will have radii that are a direct function of the time that the molten material was allowed to grow at temperatures above the solidus.

Equation (11) may also be employed to provide further insight into the nucleation rate as given by equation (8); this becomes

Equation (12)

$$N = \frac{\text{Const.}}{(t - t_E)^2}$$

Thus, the nucleation rate is shown to be inversely proportional to the time that the melt is kept above the eutectic or solidus temperatures - in agreement with observed behavior.

In applying equation (11) to equation (9), the growth rate may be rewritten as

Equation (13)

$$G = \text{Const. } (t - t_E)^2$$

Integration of both sides of this equation with respect to time, between the limits of  $t_E$  and  $t_1$  gives

Equation (14)

$$\int_{t_E}^{t_1} G dt = \text{Const. } (t_1 - t_E)^3$$

This is an expression for the total volume of all bubbles at an initial time,  $t_1$ . The total volume of voids grown after that is



Equation (15)

$$df = \left[ \int_{t_E}^{t_1} G dt \right] N (1 - f) dt$$

where  $f$  is the fraction of the gas that is contained in the bubbles. When equation (15) is integrated and equation (12) is substituted for  $N$

Equation (16)

$$f = \frac{\text{Const. } t_1^4}{(t_1 - t_E)^2}$$

Thus, the fraction of the gas that has precipitated from the melt and coalesced to form bubbles is primarily a function of the time that the melt spent above the eutectic or solidus temperatures. To a first approximation, equation (16) may be shown schematically as in Figure 4 (for the case of static solidification) where most of the bubble formation occurs before  $t_E$ . The volumetric fraction of porosity is also expressed by equation (16), except that the proportionality constant is different.

Pore Size

The expressions for  $N$  and  $G$ , equations (12) and (13), permit the calculation of the average void size,  $s$ , since

Equation (17)

$$s = \text{Const.} \left( \frac{G}{N} \right)$$

Upon substitution, equation (17) becomes

Equation (18)

$$s = \text{Const.} (t - t_E)^4,$$

or the average bubble size is directly proportional to the fourth power of the time that the melt is above the eutectic or solidus temperatures.

In this analysis of the formation and growth of pores in molten alloys, it will be noted that all of the significant parameters necessary for the understanding of this reaction have been reduced in terms of time spent at or above the eutectic or solidus temperatures. This is important because these factors may be measured with a high degree of accuracy, and the equations are thus more valid than those with some less accurately determinable parameters. Another important point is that the use of such time factors automatically provides that the parameters affecting bubble formation will be sensitive to the rate of heat transfer from the molten alloy. In other words, since the time for solidification is a function of the temperature difference between the molten metal and the surrounding solid material, the mechanism of porosity formation may be a function of the time-temperature cycles.

A similar set of equations may be derived in terms of the initial temperature of the melt and the eutectic or solidus temperature of the alloy. Such an analysis would not be as helpful in understanding these phenomena as that just given, because it does not account for the rate of heat removal.

The analysis presented here implicitly assumes that all of the gas ejected from the melt will be retained as pores in the solidified weld and that none of it would escape by outgassing (as depicted by the dynamic solidification curve in Figure 4). When this factor is taken into consideration with the simplifications made in the mathematical analysis, it is apparent that the experimental data will deviate somewhat from the theoretically predicted behavior. Where significant deviations do occur, these can be explained in terms of the parameters affecting the phenomenon in question. The thermodynamic analysis provides an insight into the mechanism of porosity formation, and furnishes a guide to the experimental verification of this phenomenon.

#### Solubility of Gases

The solubility of gases in liquid metals and alloys obeys Sievert's Law, which states that the quantity of gas in solution in the liquid is directly proportional to the square root of the partial pressure of that gas. This may be expressed as

#### Equation (19)

$$C = \text{Const. } (p)^{1/2},$$

where C is the concentration of gas dissolved in the molten metal and p is the partial pressure of that gas in the atmosphere above the melt (Reference 14). The concentration of dissolved gas, thus, may be accurately maintained if the partial pressure of the gas of interest in an otherwise inert atmosphere (such

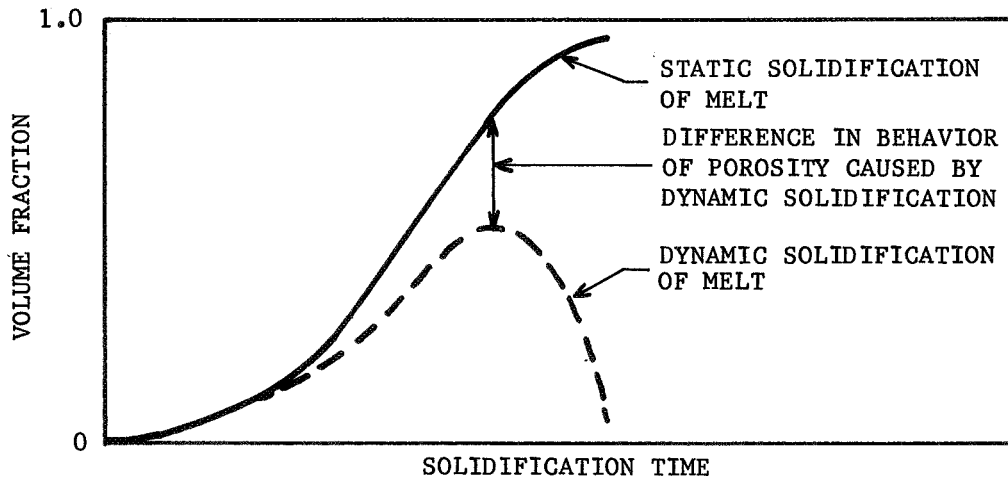


Figure 4. Fraction Volume of Available Gas as a Function of Solidification Time

as argon or helium) is controlled. The solubility of these inert gases is extremely low (References 14, 15, and 16).

The effect of variations in the amount of the dissolved gas will not change the fundamental relationships just given; it will only change the constants of proportionality.

#### Nucleation And Growth Rate Theory

The work of Johnson and Mehl (17) on the reaction kinetics of nucleation and growth processes within the solid state may be used as an analogy to approximate comparable reactions in the liquid state. This work showed that the volume fraction,  $f$ , of completion, that a given reaction attains, may be expressed as

#### Equation (20)

$$f = 1 - \exp \left( -\frac{\pi}{3} G^3 N t_0^4 \right),$$

Where  $G$  is the growth rate of the transforming material,  $N$  is the nucleation rate and  $t_0$  is the time of the reaction.

An important factor implicit in the above analysis is that the composition of the transforming system is invariant. This is not usually the case in the liquid-gas reactions under consideration here. The variation of composition in weldmetal-gas reactions is apparent because some of the gas bubbles have suitable opportunities to leave the melt under many conditions of welding. This has the effect of shifting the curve to lower apparent values of  $f$ . The amount of this shift may be determined by calculating the difference between the observed porosity and that predicted by Sievert's Law.

The non-constancy of composition of the system will also affect the observed values of  $G$  and  $N$  in equation (20). These will shift in the same direction as  $f$ . However, in the case of gases in liquid weldmetal,  $G$  and  $N$  will be less interdependent than they are in the solid state. There is a much greater probability that nucleation will be more random and not require preferred sites as is often the case in the solid state.

The growth rate of the gas pores in the liquid metal will also be much more rapid than a similar transformation in the solid state. This results from the very high diffusion rates of hydrogen in the molten metal and the rapid decrease of gas solubility in the liquid as the temperature decreases. In addition, the effects of impingement upon a phase growing in the solid state need not be considered as a limiting factor in the liquid-gas reactions in welds. When impingement occurs, the larger bubble will quickly absorb the smaller one to minimize energy. However, this factor can affect the observed values for  $N$  and  $G$  since this behavior will result in a smaller total number of pores whose size distribution is skewed toward the large diameter side.

A simplifying assumption frequently made in solid-state reactions is that the growing nucleus is spherical in shape. The fact that this is normally not the actual case often accounts for discrepancies between the observed and theoretical behavior. In the case of gas bubbles growing in a weld puddle, the

pores have a very high probability of possessing spherical shapes because they are evolving in a liquid. Those bubbles which form just above the solidus or eutectic temperatures have a somewhat lower probability of sphericity because of the increased restraint imposed by the nearly-solidified melt.

Because the times involved in the solidification of welds are several orders of magnitude shorter than those involved in most solid-state reactions, it is expected that the times available for the nucleation and growth of gas pores will be very short. This can have the effect of obscuring the influence of the large number of pore nuclei which form immediately prior to complete solidification and which do not have sufficient time to grow to observable sizes.

As the value of  $f$  in equation (20) approaches unity, the transformation of all of the matter in the system approaches completion. In the case of pore formation from the liquid phase, the value of  $f$  denotes the volume fraction of available gas (formerly in solution) which has precipitated to form pores. Under normal welding conditions  $f$  will always be less than the theoretical prediction because of the evolution of gas from the molten weld puddle. This deviation will increase as conditions, such as long solidification times, permit more gas to leave the melt. (See figure 4.)

In general, the foregoing factors have the effect of displacing the experimentally-determined curve to values lower than those which would have been predicted from equation (20). However, when allowances are made for the effects of such variables, it is possible to explain the observed data by means of an expression similar to equation (20). Experimental data obeying such a relationship will be evidence of a reaction which is controlled by nucleation and growth kinetics; it is valid even though the mechanisms of  $N$  and  $G$  cannot be described in detail.

The extent of porosity formation is usually determined by a suitable counting technique (based upon the observation of cross-sections of the solid weld). Such methods make it more convenient to refer the data to an area fraction,  $f^*$ . The calculation of this quantity is described in the following sections. Since the pores are spherical, this quantity will be directly proportional to the volume fraction when suitable statistical corrections are made.

### The Influence of Ripples

The foregoing analysis has assumed that the solidification of welds proceeds in a continuous fashion. It has been shown previously that this is not the case and that weld solidification proceeds in a discrete manner. As the successive solidifications proceed, they impose additional restrictions upon pore nucleation and growth. Both the nucleation and growth of the pores are controlled by the way in which each ripple-zone solidifies.

Thus, computations concerning porosity formation in welds must consider this behavior.

The area fraction,  $f^*$ , is approximated by

Equation (21)

$$f^* = \frac{\pi r_a^2 n}{A}$$

where  $n$  is the experimentally determined number of pores,  $r_a$  is their average radius and  $A$  is the cross-sectional area of the weld. This equation approximates the Johnson-Mehl equation up to its inflection point (assuming  $r_a$  is directly proportional to time.) This range of agreement is more than sufficient because the times required for greater completion of the reaction are those which would permit the excessive loss of gas from the melt.

The nucleation rate,  $N_R$ , of the gas pores under these conditions is

Equation (22)

$$N_R = \frac{V_R f^*}{V_p t^*},$$

where  $V_R$  is the approximate volume of the ripple zone,  $V_p$  is the average pore volume, and  $t^*$  is the average time required for the solidification of the ripple zone. The factor  $t^*$  is calculated from

Equation (23)

$$t^* = \frac{R}{S},$$

where  $R$  is the average ripple spacing and  $S$  is the length of weld made per unit time (i.e., the welding travel speed). The growth rate,  $G_R$  is given by

Equation (24)

$$G_R = \frac{4}{3} \cdot \frac{\pi f^* r_a^3}{t^*}$$

The  $\frac{4}{3}\pi r_a^3$  term is equivalent to the average pore volume. Multiplication of this term by  $f^*$  results in a  $G_R$  expression based upon ripple-zone volume, since  $f^*$  approximates the ratio of total pore-volume (per ripple-zone volume) to ripple-zone volume. Equation (24) assumes that the radii of any pores present in the melt were negligibly small at the instant that the ripple volume began to cool.

When the factors given by equations (21) through (24) are considered in terms of the Johnson-Mehl equation, the following relationship is obtained:

Equation (25)

$$f^* = \text{Const. } N_R G_R^3 t^{*4}$$

As previously noted for the more general case, the processes occurring within the ripples which conform to equation (25) are controlled by nucleation and growth kinetics. Equation (25) thus provides a means for more detailed examination of the mechanisms of porosity formation in welds.

## Experimental Procedure

A small sample of eight specimens which were available from the previous study (Reference 9) were used to test the validity of the nucleation and growth concepts. The welding conditions that were employed to prepare the samples are summarized in Table I. The bead-on-plate MIG-deposited welds were made using moisture-contaminated shielding gas (dewpoint =  $-25 \pm 5^{\circ}\text{F}$ ) so as to produce porous welds. Type-1100 filler was deposited in Type-3003 aluminum plate. Complete details of the welding procedures are described in Reference 9.

Each weld listed in Table I was used to calculate individual  $N_R$  and  $G_R$  (see equations (22) and (24)) values. This was accomplished in the following way:

1. Ripple spacings,  $R$ , were determined by macrographically viewing the weld surface at 10X magnification using a calibrated scale. Ripple-zone solidification times,  $t^*$ , were then calculated using Equation (23).
2. Ripple-zone volume,  $V_R$ , was calculated by first measuring the fusion-zone cross-sectional area,  $A$ , using a grid counting technique at 10X magnification (the section being transverse to the welding direction). Ripple-zone volumes were then determined from the following expressions:

$$(A) \quad (L) = V_T = \text{total fusion zone volume per weld length, } L$$

But  $V_T$  also may be expressed as follows:

Equation (26)

$$V_T = (V_R) \left( \frac{1}{R} \right)$$

Therefore, equating the two expressions for  $V_T$ ,

$$V_R = (R) (A)$$

3. The porosity volume fraction,  $f_{\text{vol}}$ , was obtained by averaging the X-ray fraction (previously determined in Reference 9 work) with the microscopic area-fraction,  $f^*$ , obtained using lineal analysis of metallographic cross-sections (At 10X magnification). Figure 5 illustrates a typical cross-section. No statistical corrections were made to account for the selective sampling of single cross-sections or the bias produced by predominately minor diameter pore intersections.
4. The total number,  $n$ , of pores apparent on the cross-section were tabulated. The counts were made on the 10X photomacrographs of each weld-deposit cross-sections.
5. The pore nucleation and growth rates ( $N_R$  and  $G_R$ , respectively) were then calculated using equations (22) and (24) described previously.

The pertinent experimental and calculated values are summarized in Table II.

Table I. Welding Conditions.

<u>WELD NO.</u>	<u>SHIELDING GAS (a)</u>	<u>AVERAGE ARC VOLTAGE VOLTS</u>	<u>AVERAGE ARC CURRENT, AMPERES</u>	<u>WELDING SPEED, ipm</u>	<u>SPECIFIC ENERGY INPUT Kilojoules/inch</u>
29 #11	Argon	26.5	272	40	10.8
31 #6	Argon	26.0	280	25	17.5
31 #2	Argon	26.5	275	40	10.9
21 #12	65% Helium/35% Argon	29.5	231	40	10.2
20 #1	65% Helium/35% Argon	30.5	225	25	16.5
33 #9	Helium	28.5	255	40	11.3
32 #6	Helium	29.5	245	25	17.4
31 #14	Helium	28	225	25	15.1

(a) Total flow rate = 70 CFH for all conditions.

Table II. Tabulation of Experimental and Calculated Nucleation and Growth Rate Parameters

WELD NO.	PORE FRACTIONS t*/t vol.	RIPPLE-ZONE SOLIDIFICATION Time, t*, sec.	RIPPLE-ZONE VOLUME, V <sub>R</sub> , mm <sup>3</sup>	NO. OF PORES ON Cross Section, n	NUCLEATION RATE, NR no. of nuclei per sec. per ripple-zone vol.	GROWTH RATE, G <sub>R</sub> , mm <sup>3</sup> /sec.
29 #11	0.05/0.05	0.012	2.9	181	5.8 x 10 <sup>4</sup>	7.0 x 10 <sup>-4</sup>
31 #6	0.03/0.05	0.016	6.6	460	19.3 x 10 <sup>4</sup>	2.7 x 10 <sup>-4</sup>
31 #2	0.03/0.01	0.012	3.8	135	4.0 x 10 <sup>4</sup>	0.7 x 10 <sup>-4</sup>
21 #12	0.06/0.07	0.010	3.1	410	19.5 x 10 <sup>4</sup>	6.6 x 10 <sup>-4</sup>
20 #1	0.11/0.12	0.014	4.7	157	50.2 x 10 <sup>4</sup>	6.9 x 10 <sup>-4</sup>
33 #9	0.07/0.05	0.018	10.0	344	7.0 x 10 <sup>4</sup>	11.1 x 10 <sup>-4</sup>
32 #6	0.08/0.06	0.016	8.0	487	4.1 x 10 <sup>4</sup>	17.5 x 10 <sup>-4</sup>
31 #14	0.01/0.005	0.019	9.0	36	0.2 x 10 <sup>4</sup>	3.2 x 10 <sup>-4</sup>



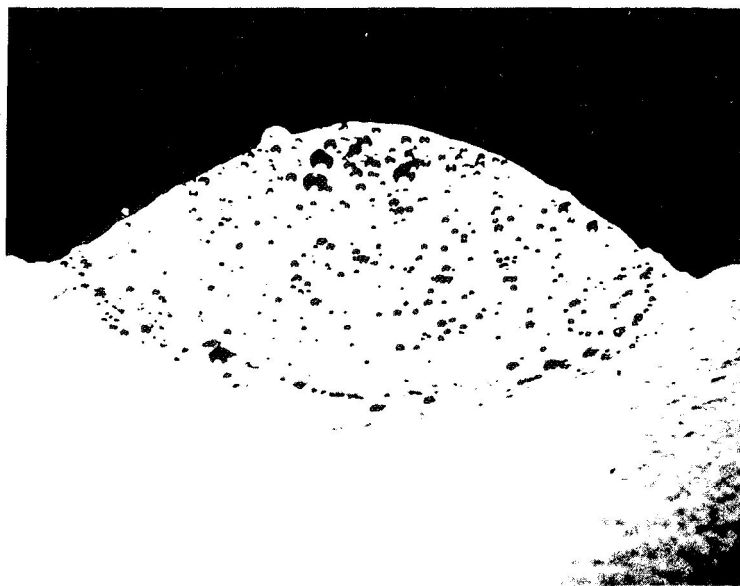


Figure 5. Electropolished Cross-Section of a Bead-On-Plate MIG-Deposited Weld in Type-3003 Aluminum Plate, 10X

### Results

The data obtained on the small number of samples is insufficient to establish any definitive functional relationships between the welding variables and solidification or porosity nucleation and growth rate parameters. Furthermore, the single cross-section measurements do not provide an adequate statistical sample. Nonetheless, interesting trends are evident and some of the tentative observations will be discussed in the following paragraphs.

Figure 6 illustrates the dependence of ripple-zone solidification time on specific arc energy. The data points for the argon and helium/argon appear to exhibit an identical functional dependence, while the helium shielded welds are different. Solidification time appears to be directly proportional to specific arc energy (the helium shielded welds do not exhibit a definitive trend).

Figures 7 and 8 portray the dependencies of  $N_R$  and  $G_R$  as functions of the square of the ripple-zone solidification time. According to the thermodynamic analysis (for a constant mass system)  $N_R$  and  $G_R$  should be directly proportional

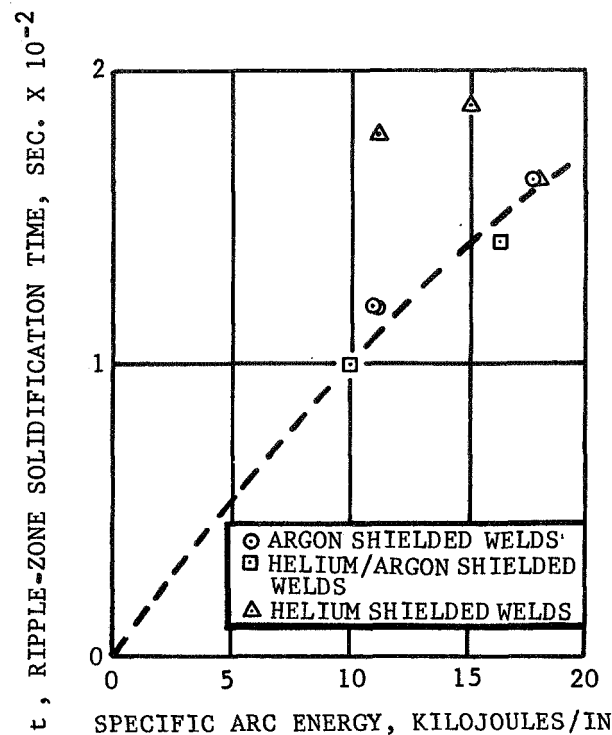


Figure 6. Dependence of Ripple-Zone Solidification Time on Specific Arc Energy

to  $t^*-2$  and  $t^*2$ , respectively. However, as explained earlier, hydrogen outgassing from the weld puddle would tend to alter the constant mass functions and displace the  $N_R$  and  $G_R$  values downward (i.e., toward lower values) for any given solidification time. The results shown in Figures 7 and 8 exhibit the expected direction of displacement. The results indicate a rather substantial outgassing effect which must be taken into account before precise functional relationships can be developed. No attempt will be made, at this time, to provide for an outgassing function.

Interestingly, the data in Figures 7 and 8 show that the functional dependencies may differ significantly for the different shielding gases. No attempt will be made at this time to explain the apparent differences.

The last and, perhaps, the most significant result to be discussed is shown in Figure 9. This figure depicts, on logarithmic co-ordinates, the dependence of the pore-volume fraction on the Johnson-Mehl nucleation and growth parameter,  $N_R G_R^3 t^4$ . As previously described, equation (25), such a logarithmic plot would be expected to portray  $f^*$  (or  $f$  vol.) as a directly proportional linear function of the Johnson-Mehl parameter (if nucleation and growth phenomenon are indeed the porosity rate-controlling factors). The results shown in Figure 9 indicate that such linear relationships do in fact exist. The argon and helium/argon shielded welds seem to fall along the same line, while the helium-shielded welds are apparently represented by an approximately parallel

line displaced downward. (This downward displacement is consistent with the generally observed lower incidence of porosity in helium-shielded welds, Reference 9). A tentative explanation for the apparently beneficial effect of helium is presented in Reference 9. Clearly, these results substantiate the contention that pore nucleation and growth phenomenon represent the fundamental factors which govern the formation of porosity in aluminum welds. Additional data are required to substantiate these findings and to fully establish various functional dependencies.

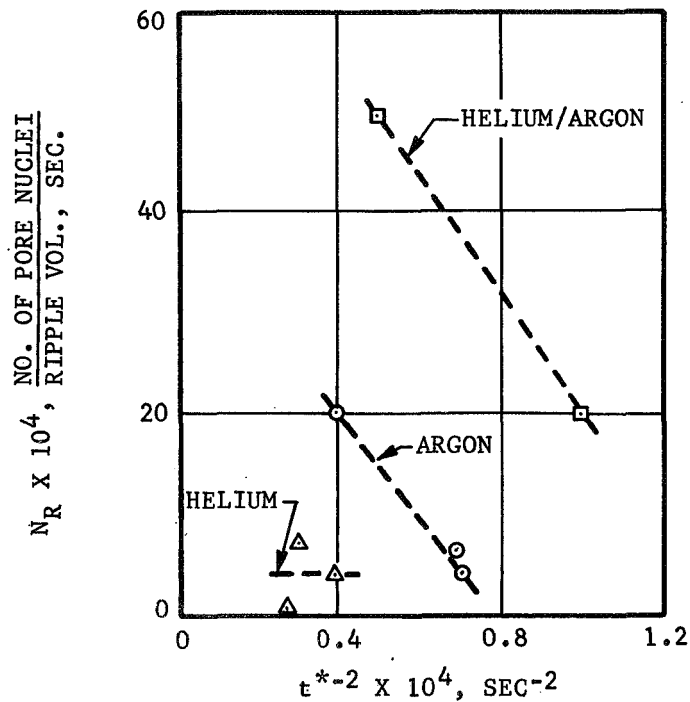


Figure 7. Dependence of Nucleation Rate on Ripple-Zone Solidification Time

#### SUMMARY

The preliminary results of this investigation have demonstrated that porosity formation in aluminum welds may be quantitatively described in terms of nucleation and growth rate theory. Unique weldmetal solidification phenomena seem to play a crucial role in the kinetics of porosity formation. It appears that nucleation and growth rates must be related to the incremental ripple-zone volume. The use of such relationships appears to provide a basis for the eventual determination of the effects of the thermal welding variables on pore nucleation and growth rates.

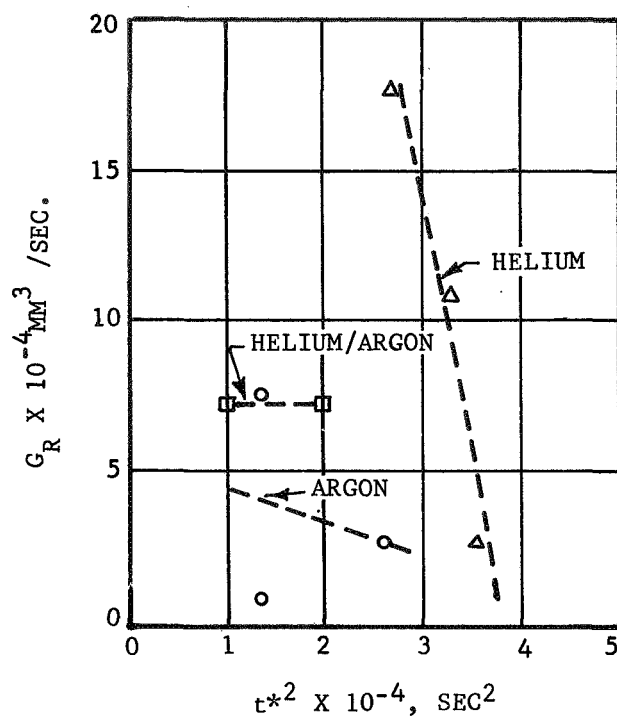


Figure 8. Dependence of Growth Rate on Ripple-Zone Solidification Time

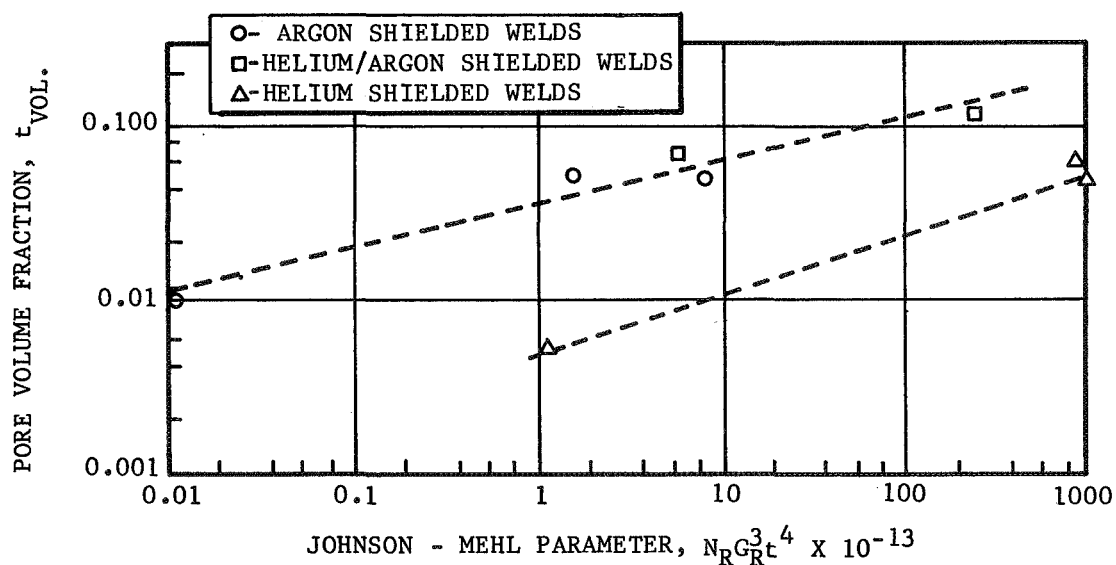


Figure 9. Dependence of Porosity Volume on the Johnson-Mehl Parameter

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## DISCUSSION

Mr. Chyle: This is a highbrow attack on this problem of porosity, and I think it's very interesting to look at it from the different standpoints, in addition to the many empirical ways we have of evaluating porosity. Now, I'm ready for questions. Who has the first question?

Mr. Saperstein: Well I object. I don't think this is highbrow at all. and I think that such a method of approach will enable us---this is my first answer to the question---will enable us to get a better understanding of what we have to control in the welding process. Now, the methods of analysis are a little different, but there's nothing highbrow about it.

Mr. Chyle: I think you misinterpreted my remarks. Let's say this is another mode of attack at a different train level, or so. Anyhow, you introduced mathematics into this thing, and I think it's very interesting. I think it's a novel way and possibly may show us the way to find the true cause of this porosity that we find so perplexing. Who has the first question?

Mr. Peterson: In the discussion this morning about porosity, there has been the word 'gas' and I think the words 'gas' and 'porosity' have been used together. What portion of shrinkage porosity can exist in the consideration that you've had in your solidification mechanisms?

Mr. Saperstein: Mr. Peterson, in our case since we use a solid solution alloy system, the shrinkage was not very substantial. We didn't have the dendritic patterns that are often encountered. I think that very little, if any, was encountered or found. In fact, I'm sure very little was found. In other cases, I think this may account for a greater percentage. One thing that I just recalled in showing you that micrograph of porosity cross section where we calculated nucleation growth rate---I didn't point it out at that time but I meant to and it bears supplement to what you said, the pores were

frequently distributed in little circles. You've seen this, I'm sure, a hundred times in welds where these circular patterns appear. This is the intersection of the wave front with that plane, and it has to give a sort of circular pattern.

Mr. Chyle: There's a question in the back of the room, Yes?

Mr. Martin: In your work, did you make any studies of the mechanical strengths in welded and unwelded ratio of the specimens with various degrees of porosity?

Mr. Saperstein: Mr. Martin, in this particular program, we did not. However, in subsequent programs, we have looked at this and will be coming up with some observations at a later date. We're just in the early stages. I think one of the contracts that NASA is awarding will deal with this in great detail.

Mr. Brown: If I understood you correctly, I don't agree with you. I think you said that you were using a solid-solution type alloy. Is that correct?

Mr. Saperstein: Approximately; this is not exactly correct.

Mr. Brown: Well, in solid-solution type alloy, shrinkage is very prevalent, probably more prevalent than in any other type of alloys. This tends to be confused quite often with micro porosity, since micro porosity not only promotes but grades into micro shrinkage. So, the gentleman's question about shrinkage, I think, was well taken.

Mr. Saperstein: Well, I'm not sure this is so; it may or may not be.

Mr. Brown: You may check the Literature and find out.

Mr. Saperstein: In the case of the solidification of the weld deposit, we do have--- I think we have to all recognize this---a heavy concentration of



solidus elements in certain regions. It's not a uniform distribution. In the first place, the ripple zone volume means we're having solidus segregation. The formation of dendrites means that we're having solidus segregation. The regions around the solidus segregates and the more pure material will have different shrinkage characteristics. Frequently, we will see at these interfaces, small shrinkage cavities, and I'm not sure whether we see more of them in this case as opposed to the case where we have a single phase or approximately a single-phase alloy. I won't quarrel with the statement. I have no quantitative data at the moment. In this case, of course, they were all spherical, virtually one hundred percent.

Mr. Chyle: Another question on the third row?

Comment: I think Phil is to be congratulated, here, for taking a nucleation and growth approach. There are a couple of remarks I'd like to make, tying in the things he's presented, plus some things that Perry Rieppel said. Earlier this year at the AIME meeting in February, Rondike and Hess presented two papers that related to nucleation of gas. We have essentially confirmed these results in our own facility. And quite briefly, these indicate the following: if under vacuum you solidify molten aluminum which is essentially clean and free from non-metallics, such as hydrocarbon oxides and the like, and a melt which is not free from these materials, there will be an indication of hydrogen in the aluminum containing the non-metallics but not in the material free of non-metallics, suggesting that there can be heterogeneous nucleation here, too, due to irritation of non-metallics. I think this can also be a consideration since we're talking about a rate phenomena in the welding process.

Mr. Saperstein: I think that's right, George. Of course, recrystallization phenomena is in a sense heterogeneous nucleation.

Mr. Chyle: We're running just a little behind schedule so we'll turn off the discussion at this stage, and we want to thank Mr. Saperstein for a most interesting paper.

OBSERVATIONS ON POROSITY  
IN ALUMINUM WELDMENTS

By

F. R. Baysinger

KAISER ALUMINUM AND CHEMICAL CORPORATION  
SPOKANE, WASHINGTON

## INTRODUCTION

In a recent survey of welding difficulties in the aerospace industry, welding porosity of aluminum weldments was one problem common to all fabricators. Inasmuch as the Department of Metallurgical Research of Kaiser Aluminum has been studying weldment porosity for some time, we believed that some of our observations might be helpful to those persons in the aerospace industry who must produce high quality weldments. Accordingly, we have reviewed previous research work conducted by our laboratory, and in the literature relating to the improvement of aluminum weldment quality, and have assembled the following notes and observations related to the subject. All DMR data were previously developed by Kaiser Aluminum at private expense and not as a part of this contract.

## POROSITY IN MIG WELDS

The basic cause of porosity in aluminum welds is gas entrapped by the freezing weld metal before it has a chance to rise out. The source of this gas may be entrapped shielding gas, air, other gaseous contaminants in the puddle as a result of violent arc action, or it may be dissolved hydrogen. The amount of gas remaining in the weld pool is a function of the cooling rate of the weld puddle. Table I shows various causes of porosity and some corrective measures. The mechanism of porosity is discussed in detail in the following sections.

### Entrapment

Shielding gas, air, or other gaseous contaminants can be entrapped in the weld puddle as a result of violent arc action. This is similar to the entrapment of air bubbles in a glass of water being filled from a faucet. If the glass of water could instantly freeze, there would remain within the ice a considerable amount of gas which would appear as porosity. Porosity in a weld is formed in a similar manner. The turbulence of a weld pool is affected by the characteristic of the droplet transfer. If too low a welding current is used, so that large globules of metal transfer across the arc, more turbulent puddle reaction will occur than if fine, small well-formed droplets transfer. Magnesium alloys inherently have a metal droplet which is irregular in shape and violent in its motion in traveling across the arc. A pool resulting from such a droplet will be subject to more agitation and, hence, more entrapment of gas. Excessive welding currents can entrain gas by merely depositing metal over a gas bubble which freezes before the entire bubble escapes. This latter type of porosity is generally very irregular in shape.

### Hydrogen

In addition to entrapment, another major cause of gas porosity in aluminum welds is hydrogen. Molten aluminum has a fairly high affinity for atomic hydrogen and readily dissolves it, as is shown in Figure 1. On the other hand, solid aluminum can contain very little hydrogen. In a weld, hydrogen gas is rejected as the weld puddle freezes. If the cooling rate

Table I. Some Possible Causes And Suggested Corrective Measures  
For Porosity in MIG Metal

<u>Basic Cause</u>	<u>Contributing Factors</u>	<u>Suggested Corrective Measures</u>
Entrapment	Turbulence of weld pool. Excessive current entrains gas.	Use higher welding current to stabilize droplet transfer. Reduce from excessive current, slower travel.
Hydrogen	Oil or other contaminants on filler wire. Hydrated oxide film on filler wire. Oily drive rolls or liner in MIG gun. Wet shielding gas. Water leaks in MIG gun. Oily plate. Spatter particles ahead of puddle.	Protect wire in shop with covers. Do not open dessicated plastic packaging until ready for use. Do not use wire which has been kept for any length of time outside of dessicated storage. Clean rolls with solvent, change liner. Check dew-point of gas. Reject bottles above -40F dew-point. Repair guns which have been overheated due to water failure. Clean plate. Adjust welding conditions so spatter is minimized.
Cooling rate of weld pool	Rate of heat input into the weld. Too rapid a rate of heat extraction from the weld. Fluidity or viscosity of the welding pool. Fast freezing rate of weld pool. Temperature of back-up bar, if used. Groove configuration of back-up bar, if used. Excessive current.	Use higher welding current and/or a slower speed. Preheat sometimes helps. With Mg-containing fillers, which are less fluid than 4043, trace amounts of chlorine in arc will increase fluidity. Higher current, slower travel and preheat all decrease freezing rate. Hot back-up bars reduce root porosity. Shallow wide grooves preferable to deep narrow grooves in the back-up bar.
Erratic wire feeding	Drive roll slip. Excessive bending of guide liner. Bent contact tube. Kinks in wire. Gallling in contact tube. Electronic "hunting". Wrong size liner.	Increase pressure on rolls, change to knurled roll; change to V-groove roll rather than U-groove; right diameter U-groove roll. Change position of MIG unit to reduce necessity of bending cable to gun. Replace thyatron tube or bias battery.
Quality of base material	<u>Castings</u> - Dross Porosity <u>Wrought</u> - Lamination	Change foundry technique to obtain sound castings. Very rare occurrence. Reject plate or sheet material.
Other	Partial penetration joint. Multipass welds.	Use full penetration joint. Increase fillet size to compensate for line of root porosity if critical application. Go to high current density single pass per side technique.

of the weld puddle is fast, the hydrogen cannot bubble out to the surface. Instead, it is held within the metal as it freezes, forming gas porosity.

To demonstrate how the presence of hydrogen in the arc causes porosity, a number of tests were conducted by DMR several years ago in which hydrogen and hydrogen-containing contaminants were added to the MIG arc in varying amounts. The contaminants included hydrogen, propane, and water additions to the shielding gas. Hydrated oxide coatings on the weld wire were also used as a source of contaminant. In every case, with an increasing amount of contaminant, there was an increase in the level of weld porosity. Figure 2 shows how hydrogen additions to the shielding gas affected porosity. Typical weld porosities obtained by water vapor and propane additions to argon shielding in a MIG arc are shown in Figure 3, as well as dross caused by oxygen additions.

Hydrogen in any chemical compound on the filler wire appears to be the main source of hydrogen in MIG welding. For example, if the filler wire is processed or stored in such a manner that hydrated aluminum oxide film remains on the wire, porosity will occur in the welds made with that wire. Poor welds result from using wire which has been stored for a long period of time under humid conditions where atmospheric moisture can combine chemically or be absorbed by the aluminum oxide film. Figure 4 shows the deterioration in radiographic quality of welds made with filler wire exposed for eight months to ambient Spokane atmosphere. The radiographic standard for comparison of A to D weld radiographic quality is given in Figure 5. Hydrogen-containing compounds on the wires, such as oil, drawing compound, shop grease, etc, will cause porosity. The weld wire surface is the major source of weld contamination. The high ratio of wire surface area to the volume of deposited weld metal introduces a large concentration of contamination into the weld.

Other possible sources of hydrogen contaminants include the base material and the shielding gas. Hydrated oxides, oil and certain other contaminants can be a cause of weld porosity in thin materials. Spatter ahead of the weld puddle can also cause porosity.

Contamination can occur in an occasional bottle of shielding gas which is wet from moisture leaks in the welding torch, or from gas line systems which have absorbed moisture. Metal lines are recommended.

It is desirable that the filler alloy welding wire be produced by a method which insures a low level of hydrogen in the wire. The filler should be free of heavy hydrated oxide films, oils, or other surface contaminants, and the surface should be smooth. Wire should be packaged in a vapor barrier container with dessicant or dry gas to prevent deterioration during storage in moist atmospheres. Such packaging of weld wire assures relative freedom from shelf life deterioration and if used within a reasonably short time after removal from the package, the wire will not deteriorate further.

The fabricator cannot at the present time be sure of the quality of aluminum welding wire, even when it is packaged adequately. The wire can, however, be qualitatively inspected prior to use. The following paragraphs describe some of the checks used by the Department of Metallurgical Research of Kaiser Aluminum & Chemical Corporation to evaluate welding wire quality.

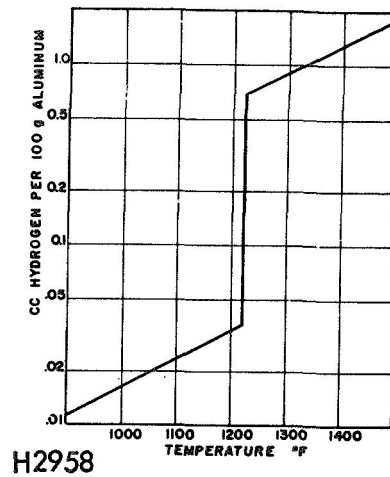


Figure 1. Solubility of Hydrogen in Aluminum

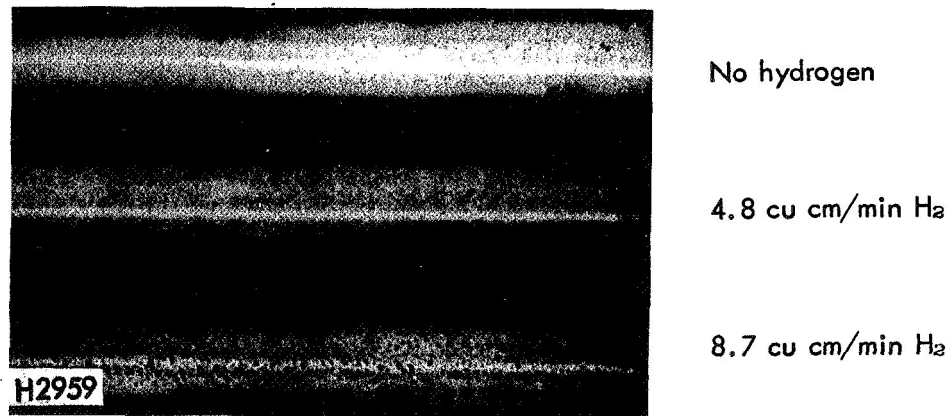
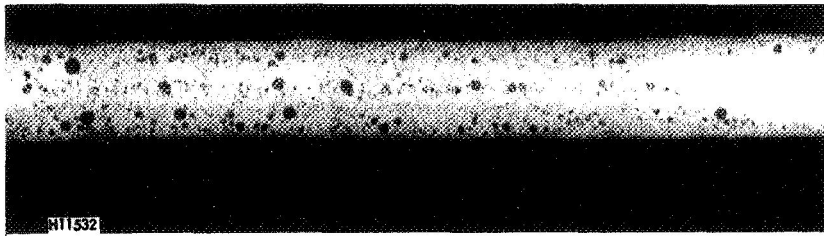
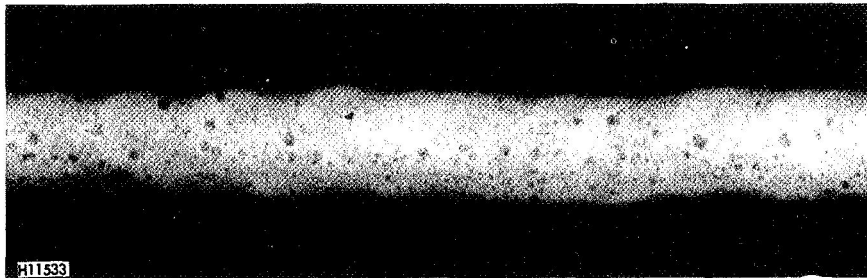


Figure 2. Effect of Hydrogen on Weld Porosity

Radiographs showing increase in porosity in a MIG weldment with increasing amounts of hydrogen added to argon shielding gas.

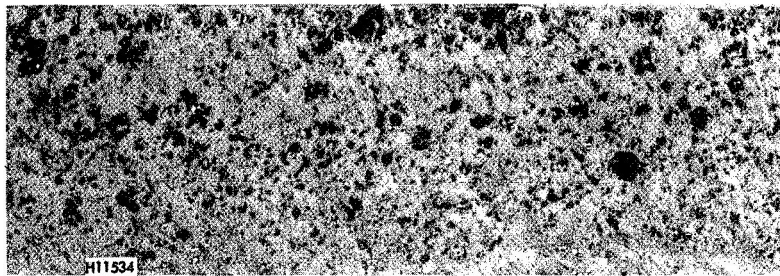


1.4 g/min water vapor



1.3 cu cm/min propane

Radiographs



2.0 cu cm/min oxygen

Fracture

Figure 3. Effect of Contaminants in Shielding Gas

MIG welds made with contaminants added to argon shielding gas.

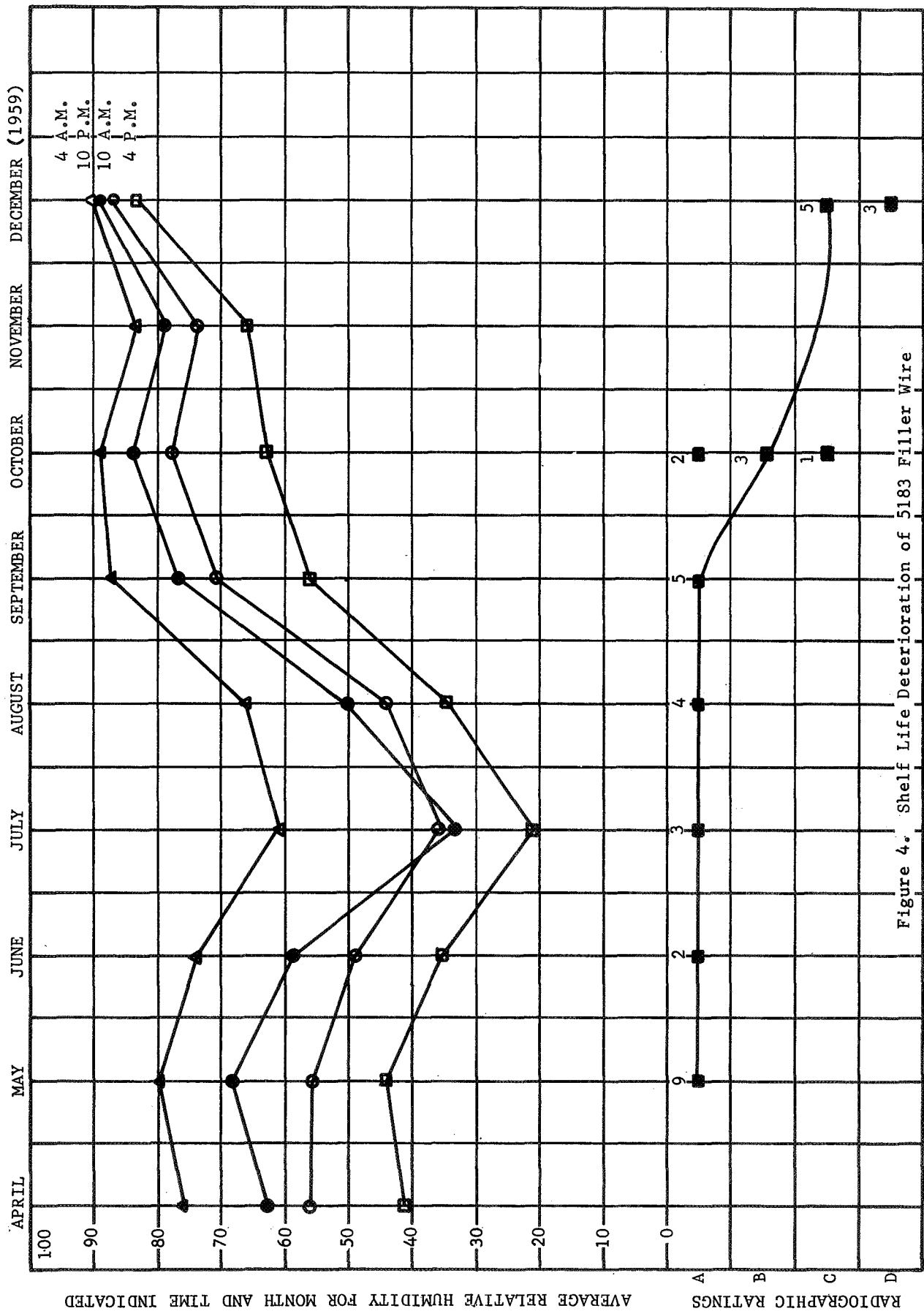
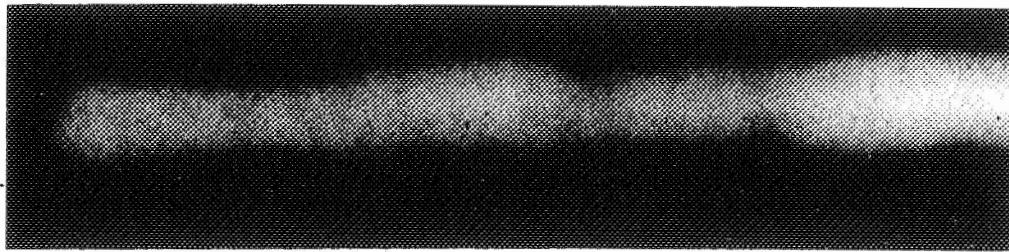


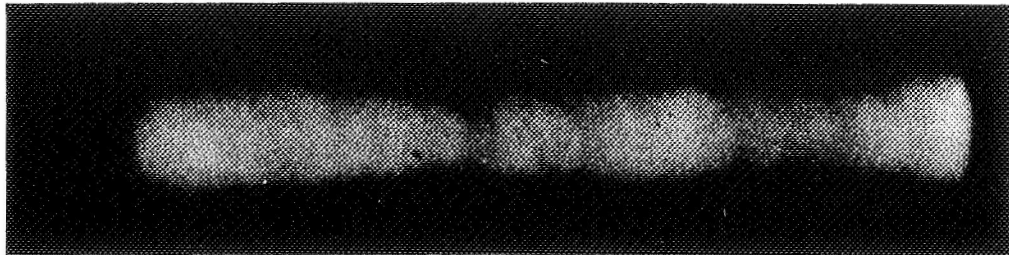
Figure 4. Shelf Life Deterioration of 5183 Filler Wire

RELATION OF RELATIVE HUMIDITY TO CHANGES IN RADIOGRAPHIC QUALITY OF WELDMENTS MADE FROM 5183 ALLOY WELD WIRES STORED IN UNHEATED OUTDOOR STORAGE CABINETS IN SPOKANE. NUMBERS ARE THE NUMBER OF WELDMENTS EVALUATED IN OBTAINING THE RATING INDICATED.

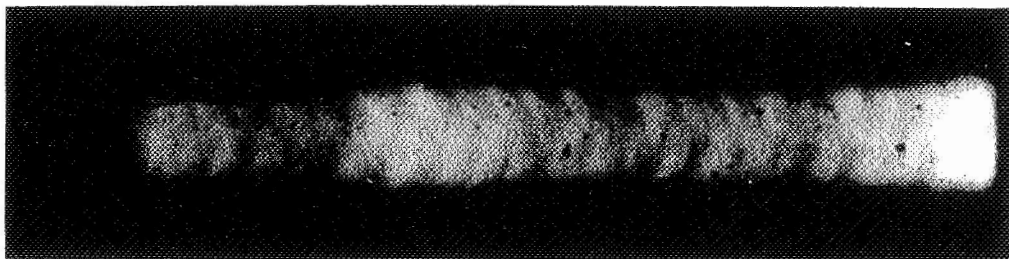




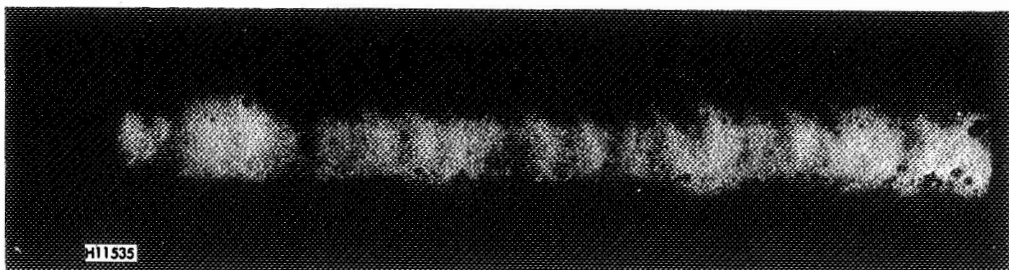
A Rating



B Rating



C Rating



D Rating

Figure 5. DMR Radiographic Porosity Standards for Aluminum Welds

Developed and used in the welding laboratories of Kaiser Aluminum & Chemical Corporation.

1. The wire surface should be free of chips, nicks, gouges, and cold laps. Figure 6 shows a typical cold lap in a welding wire. Such a condition can entrap drawing compound, which in turn results in excessive weld porosity. Die-shaving should be concentric so that the oxides are removed from the entire circumference. Figure 7 shows the appearance of an eccentrically shaved wire, with a heavy oxide stripe remaining. Welds made with this wire were drossy and porous.

2. Surface contact resistance is a qualitative indication of wire oxide film thickness. We use a Smith VT-II Analyzer modified with a one-inch area cylinder, and a standard clamping force of 10 psi on crossed wires, obtaining three to ten readings are obtained per sample. Relative oxide film thicknesses are empirically defined as follows:

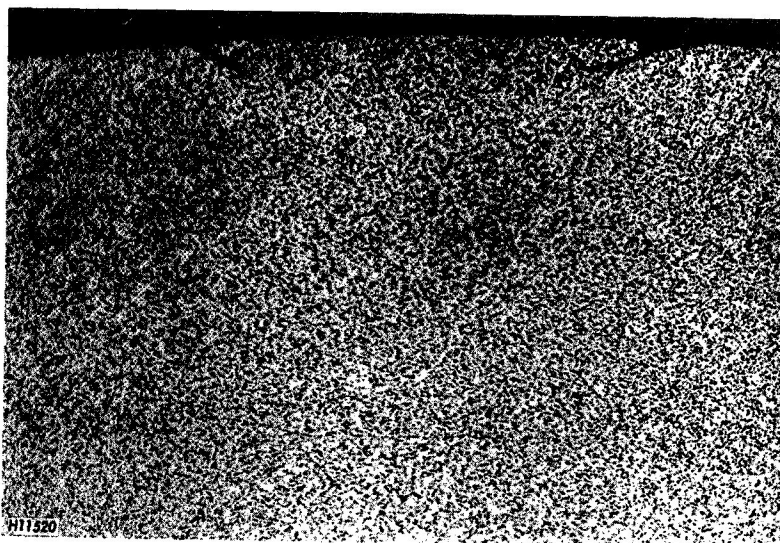
Thin film	Up to 500 microhms
Medium film	Up to 5,000 microhms
Thick film	Exceeding 5,000 microhms (usually more than 10,000 microhms, or off-scale of instrument)

(Wires which have medium or thick films should be checked by means of a weld test, to determine if the coating is hydrated.) The contact resistance method is most useful in determining deoxidation practice. Wires with as low readings as possible (50 to 100 microhms) generally give sound quality welds.

3. A flame test may be used to visually assess the comparative surface film thickness of weld wires, and also the internal quality. A strand of wire is carefully heated in a reducing oxyacetylene flame, and the surface appearance of the wire observed. Figure 8 shows the appearance of weld wires which have a heavy oxide film thickness. Figure 9 shows the appearance of wires with a thinner oxide coating, but which is hydrated. Figure 10 shows a longitudinal cross section through a random sample of weld wire after flame testing, showing the extreme amount of gross internal porosity which occurred. Sometimes gross porosity does not form, but excessive shrinkage microporosity is observed after flame testing, as shown in Figure 11. Both wires produced welds of D radiographic quality or worse. (See Figure 5.)

4. Metallographic examination of the wire may show the presence of inclusions or voids which may be the cause of weld porosity. Figure 12 shows the microstructure of two wires of the same Al-Mg-Zn composition. One produced a sound weld, and the other produced a porous weld.

5. In work requiring radiographic inspection, it is desirable to check the quality of welds made by the filler wire before the wire is used on the production part. It is a relatively simple matter to take clean aluminum material of the same alloy as to be used in production and make a three-pass fillet weld, cooling between each pass. The fillet weld may then be broken open and examined for porosity. Some typical fillet weld fractures are shown in Figure 13. A quality of at least Grade II is required for most work. It is also possible to deposit several successive

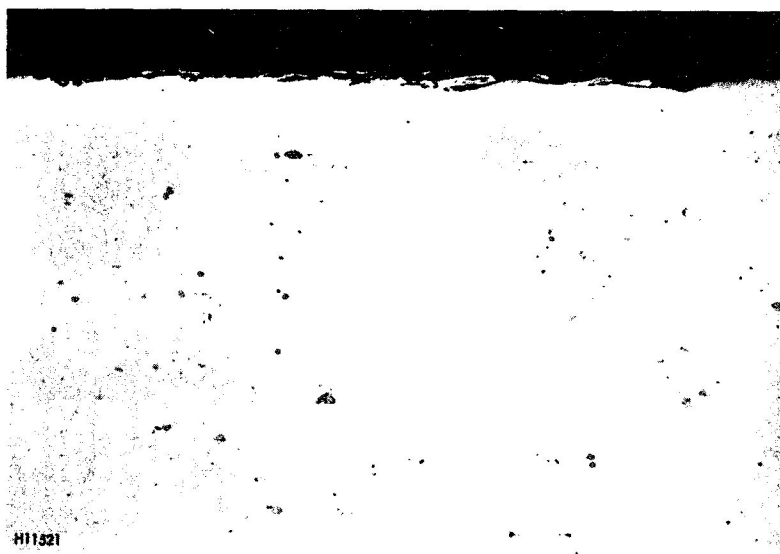


Hot Phosphoric

500X

Figure 6. Cold Lap in Welding Wire

Transverse cross section through random sample of  
3/32-inch 2319 filler wire.

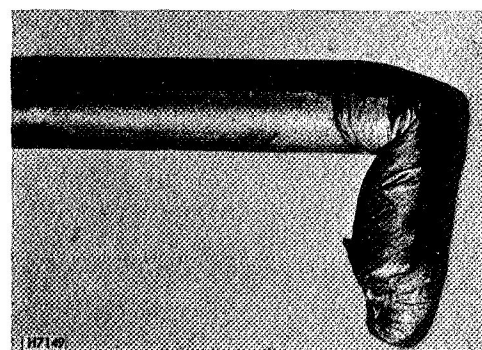
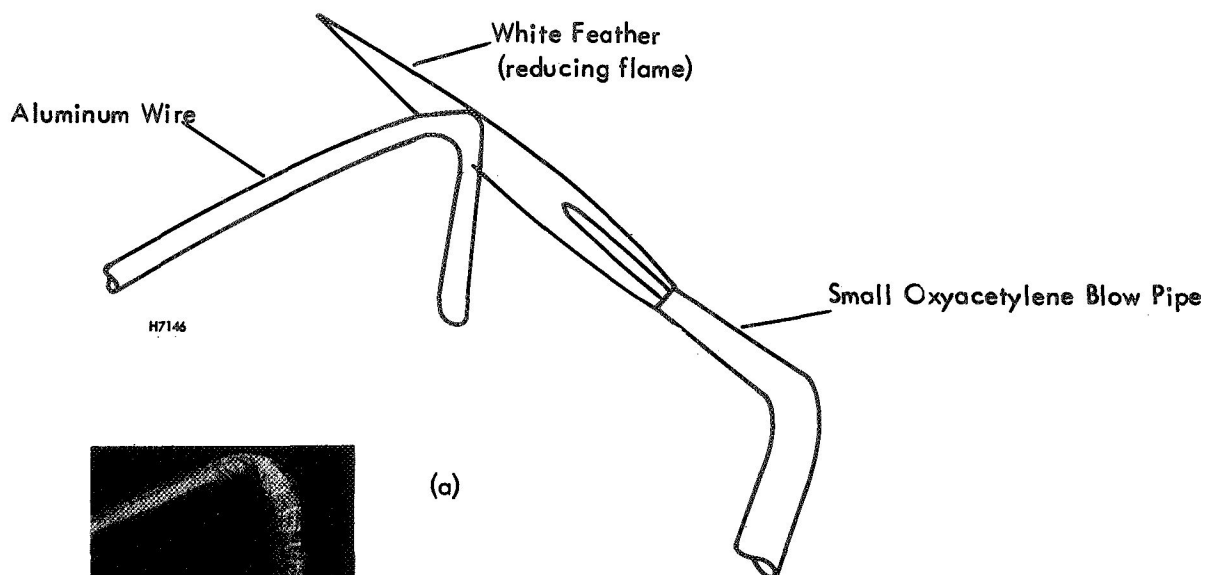


Unetched

500X

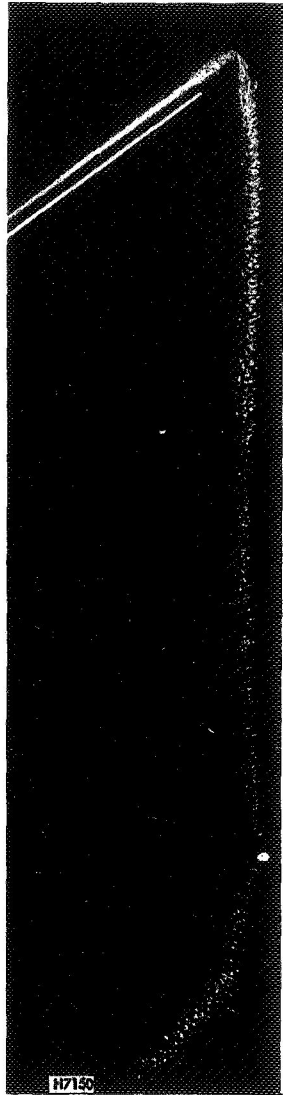
Figure 7. Longitudinal View of Wire Surface Oxide

Wire was eccentrically shaved, resulting in a stripe  
of heavy oxide remaining on one side. Experimental  
Al-Zn-Mg filler alloy.

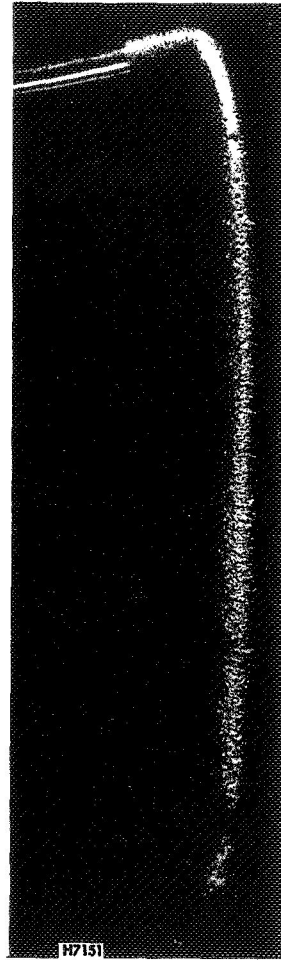


- (a) Flame test is conducted using a reducing oxyacetylene flame.
- (b) Heavy oxide on wire gives a broken macaroni effect.
- (c) Heavy oxide on wire shows blistering from hydration.
- (d) Appearance of extremely heavy surface oxide.

Figure 8. Flame Testing Aluminum Weld Wire



4X

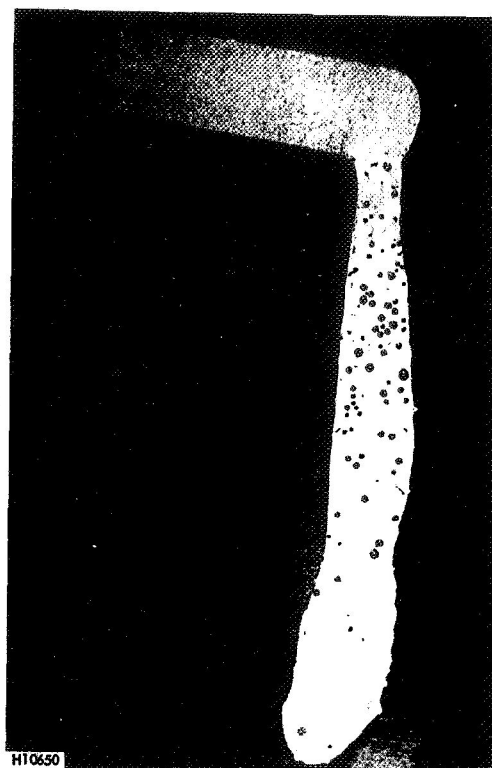


4X

Figure 9. Wires Heated in Oxyacetylene Flame That Show Evidence of Hydrated Oxide

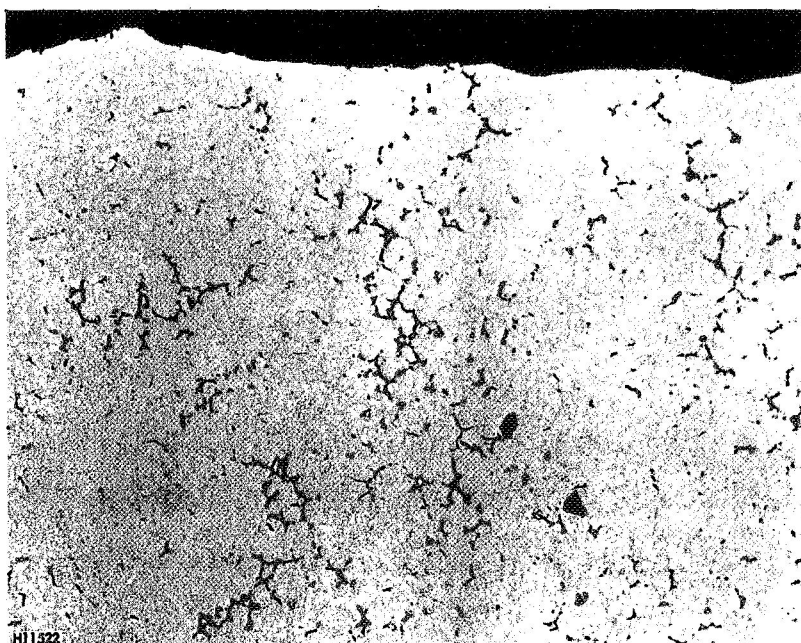
Wire on left has less moisture than wire on right.

This wire, although giving low surface contact resistance values, still indicated severe blistering upon flame testing. The amount of internal porosity which resulted was severe.



HA

Figure 10. Longitudinal Cross Section Through a Weld Wire Which Has Been Flame Tested



TING

Unetched

100X

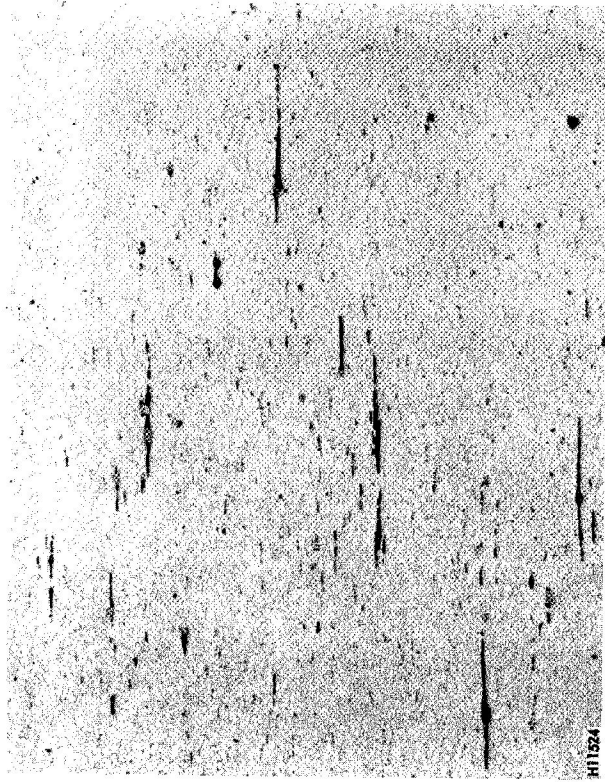
Figure 11. Shrinkage Porosity in 2319 Weld Wire after Flame Test Melting



Unetched

250X

Wire producing sound weld.



Unetched

250X

Wire produced weld shown below.

Wire on right showing microstructural defects was deoxidized to 50 microhms, but still produced a MIG weld of the quality shown at lower right.

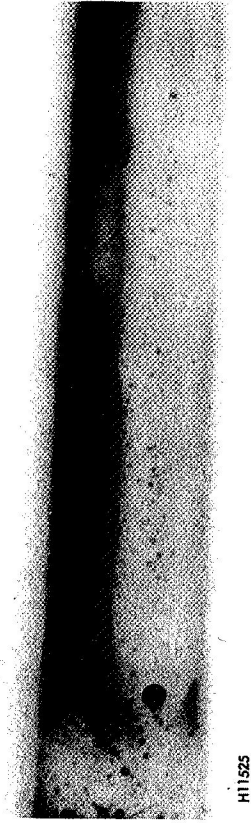


Figure 12. Longitudinal Microstructure of Al-Mg-Zn Filler Alloys



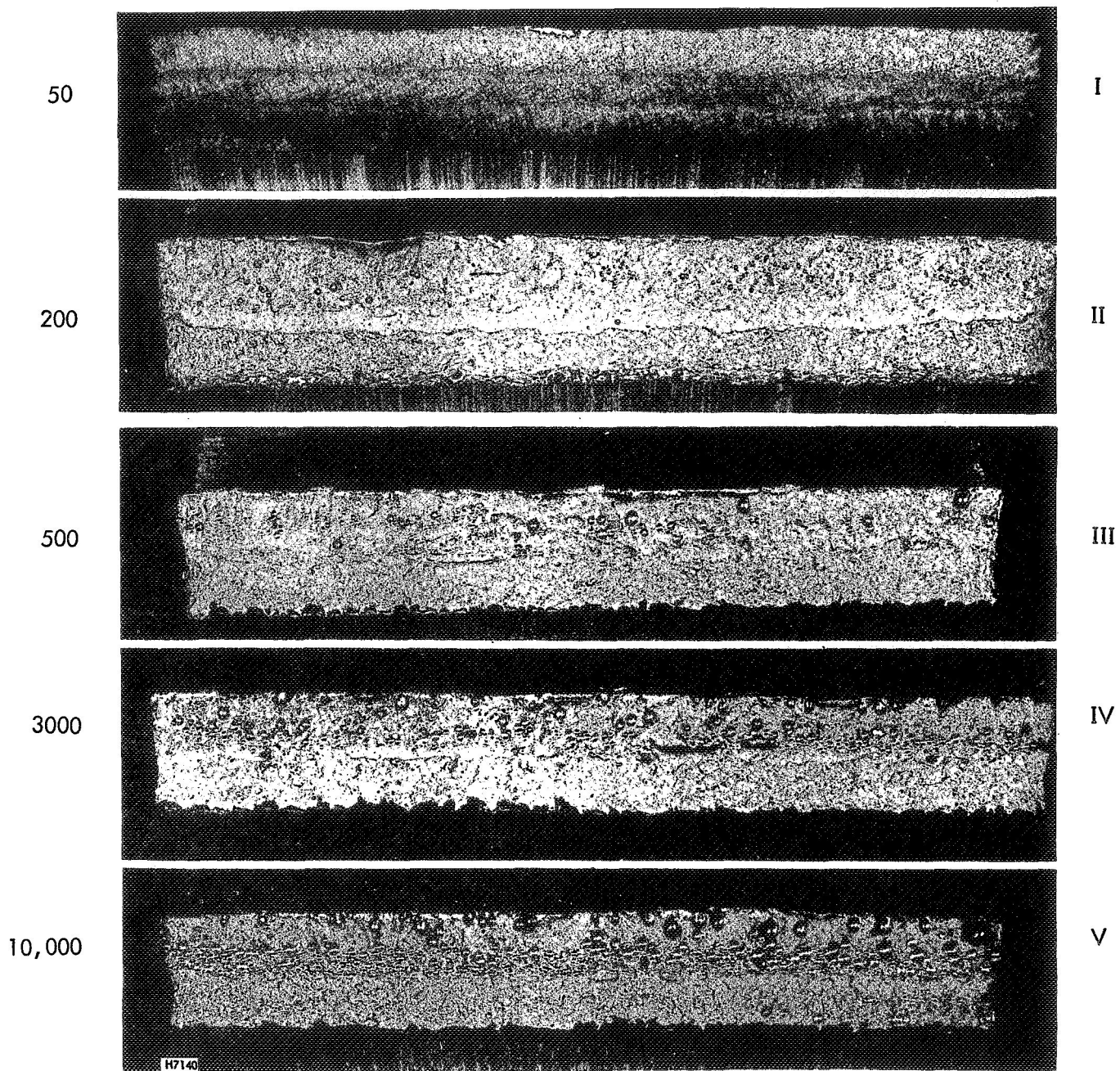


Figure 13. Fillet Weld Fracture Porosity Standards

Department of Metallurgical Research  
Welding Engineering Branch



layers of weld metal on a flat plate or make a butt weld, either of which can be broken open or radiographed. This will assure that the quality of filler wire being used is adequate for the job. Preweld checking may also show defects with the equipment, the welding procedure, etc.

Occasionally, a gas bottle may have a dew point considerably higher than -40F. In the case of the welding torch, improperly seated O-rings, loose fittings, warped ceramics, torches which have been overheated so that solder joints leak, use of hoses for the shielding gas which have previously been used for water lines or use of old rubber hoses, are all conducive to moisture pickup in the shielding gas. The vapor content of the gas escaping from the torch nozzle can be checked by determining its dew point. A molecular sieve tower in the gas line is good insurance against moisture pickup in the gas stream.

### Cooling Rate of Weld Pool

(The following comments on gas motion within a puddle apply to flat or vertical position welds. In horizontal or overhead welds, the gas tends to be entrapped.)

The amount of gas remaining in the weld pool is a function of how fast the weld pool solidifies. The rate at which gas escapes from a weld pool is determined by the amount of time the gas bubbles have to rise to the surface. If most of the gas has time to escape before the weld pool solidifies, the weld will have less porosity and be of generally good radiographic quality. The time during which the weld pool is molten is determined by the heat input into the weld, the rate of heat extraction from the weld, the fluidity or viscosity of the weld pool, the freezing rate of the weld pool, the temperature of the surrounding material, the temperature of the back-up bar used, and the groove configuration of the back-up bar.

Slowing down the cooling of the weld puddle by increasing the heat input into the weld can be accomplished by increasing the current or decreasing the travel speed, or both, within the operating limits conducive to proper bead deposition and contour, and the thickness limitations of the base material. Use of higher arc voltage is beneficial in MIG welding. Helium may be added to argon in amounts over 10 percent to increase arc voltage and reduce porosity. The rate of heat extracted from the weld is generally fairly high due to the high conductivity of aluminum. Obviously, with heavier, thicker sections more heat is absorbed than with thinner sections. The cooling rate can be slowed by preheating, although preheating may reduce mechanical properties as a result of annealing or overaging of the parent metal or heat-affected zone.

Weld metal cools from the outer edges toward the center of the weld nugget. It frequently happens that the cooling rate is such that porosity is frozen in along the fusion line, often giving rise to the sometimes erroneous conclusion that such porosity came from the base material. A wide weld bead, having a thin feather edge at its width extremities can have a line of porosity at the edges due to fast freezing of the thin section of weld metal. This will show as line porosity in a radiograph and is associated generally with multipass stringer-bead type welding.

The fluidity or viscosity of the welding pool will affect porosity. For example, a weld deposit of 1100 alloy has an instantaneous freezing rate, whereas 4043 has a more fluid puddle with a broader freezing range. Weld metal from a filler containing magnesium or zinc may be less fluid due to the presence of heavier surface oxide films on the weld puddle. The freezing rate of the weld pool is a function of the alloy, 1100 being almost instant freezing and 4043 and 5000 alloys having slower freezing rates. Other inter-related factors such as the travel and preheat will affect the freezing rate slightly. Use of negative ion oxygen or chlorine additives to the shielding gas apparently increases fluidity.

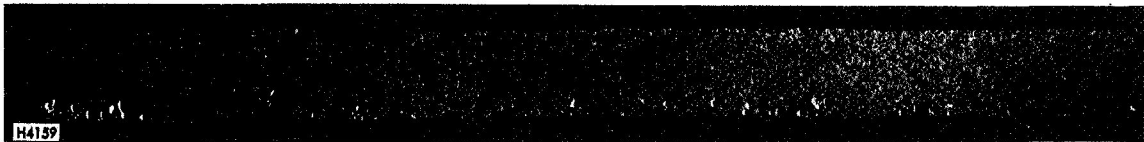
Root porosity may be obtained in a weld made with a back-up bar if the wrong groove configuration is used. A deep narrow groove in a back-up bar is conducive to root porosity, whereas a wide, shallow groove tends to minimize porosity because of the larger mass of weld metal at the root. Typical root porosity is illustrated in Figure 14. Preheating of the back-up bar has been found by some fabricators to further reduce the tendency toward root porosity.

### Erratic Wire Feeding

Erratic wire feeding can cause porosity in a weld metal. Erratic feeding can be due to a number of things. The weld wire may slip in the drive rolls. Slipping can be due to insufficient pressure, use of U-grooved roll which is of too large or too small a diameter for the size wire being used, or too excessive bending in the guide tube of the gun. To correct these things, it is possible to change to a V-groove drive roll or to the right diameter U-groove roll. Excessive bending of the cable leading from the MIG welding wire drive unit to the MIG welding gun can cause excessive friction on the filler wire in push type guns and cause erratic wire feeding. Bent contact tubes in the MIG gun may cause excessive friction and stitching. Kinks in the wire will jam in the gun and cause a burn-back, or if they feed through, will cause a momentary slowing of the wire. Improperly wound spools with "cross overs" or edge bound strands can also cause erratic wire feeding.

Aluminum wire can seize and gall inside the contact tube causing an erratic or stitching arc action. Replacing with a new contact tube will correct this situation. Electronic hunting sometimes occurs. This can be due to a dead bias battery so that no arc control is obtained or to mechanical factors such as worn drive roll bearings, a defective thyatron tube, or other troubles in the circuit such as shorted resistors, defective relays, etc. If the wire speed is too low, the drive motor may have insufficient torque to maintain even speed. Use of the wrong size liner or guides can cause erratic wire feeding, particularly if a wire size larger than is recommended for the liner is being used.

Welding current can affect porosity. Where the welding current is too low, an erratic arc transfer occurs, resulting in excessive turbulence of the pool and increasing the likelihood of porosity. It has been observed that extremely short arc lengths are conducive to weld porosity. A short arc length generally occurs with low voltage. Short arc lengths also occur with mechanical stitching on the weld wire, and porosity occurs at the points



Hot Caustic

3X

Figure 14. Example of Root Porosity  
Line of root porosity in weld deposited against  
unheated backing bar.

where the arc was short. It should be remembered that smaller diameter wires have shorter arc lengths than larger diameter wires, so that an arc length which is normal for 0.020-inch diameter wire would be short for 3/32-inch wire.

### Quality of Base Material

Porosity can be related to the quality of the base material, particularly in castings. A "boiler effect" can occur where the weld metal heats a volume of gas from a lamination in the base material, forming porosity as shown in Figure 15.

Plate materials sometimes appear to have a tendency to out-gas when melted in a furnace or in an arc. There is often a sufficient quantity of gas to cause porosity in DCSP-TIG welds. An example of porosity formed upon melting, compared to that observed in a TIG-horizontal weld in the same material, is shown in Figure 16. It has been suggested that a melt test sample be taken from production material and correlated with radiographic results, with the goal of establishing how much gas can be tolerated without weld difficulty. The quantitative effect of gas content vs. weld quality is a major research area which has not yet been properly studied.

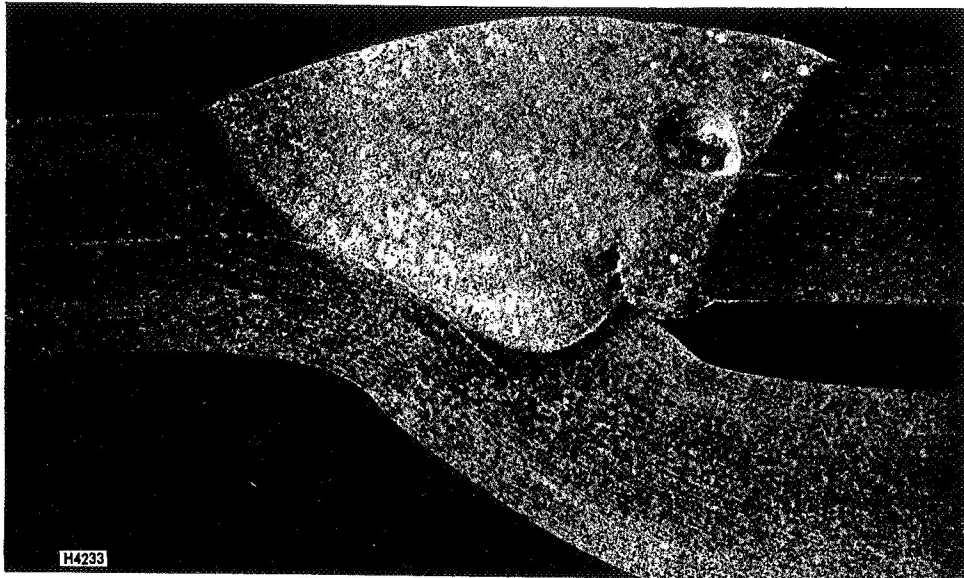
Microfissures in the heat-affected zone apparently can be inflated by hydrogen gas pressure. Hydrogen would tend to lie in the last-to-freeze metal areas of low-melting eutectic. The heat of welding not only melts these low-melting stringers, but expands the hydrogen there as well, giving an effect as shown in Figure 17. A similar effect was noted by Nikiforov (Reference 7) in describing porosity in a 6 percent Mg alloy.

### Multipass Welding

Porosity is more prevalent in multipass welds than in single pass welds. Apparently, successive beads pick up gas contamination from preceding beads, and cause a cumulative effect. Thus, top passes of welds in heavy plate have been observed to contain more porosity than root passes. Wherever practicable, welds with a minimum number of passes should be used. High-current density techniques make possible MIG butt welding with a single pass per side in aluminum plate up through 1-1/4 inches thick. Similarly, DCSP-TIG weldments can be made in a single bead in plate up to 3/4-inch thick in some alloys.

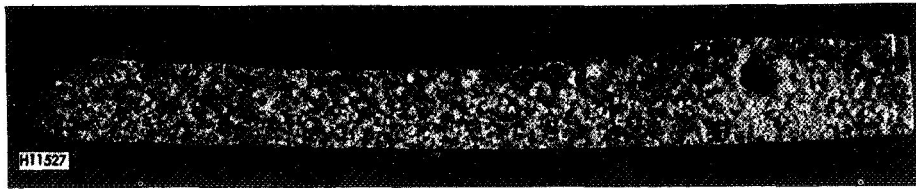
## EFFECT OF WELD METAL POROSITY ON MECHANICAL PROPERTIES

One question frequently asked by fabricators is, "What effect does weld porosity have on the properties of aluminum welds?" As shown in Figure 18, considerable porosity can be tolerated in a weld, before there is much effect on mechanical properties. The level of porosity can be extremely high before tensile properties drop off appreciably. Data shown are for MIG weldments in 5083 plate where different porosity levels were obtained by contaminant additions to the MIG welding arc. The effect of porosity on fatigue properties of weld metal would be expected to be more deleterious.

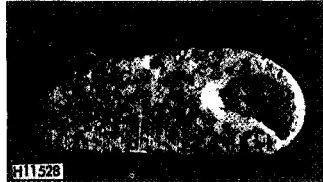


10X

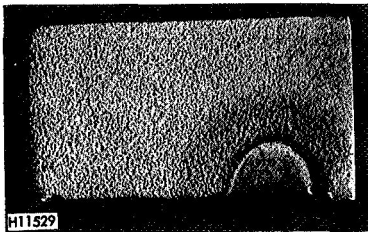
Figure 15. Porosity in Aluminum Weldment Caused by Lamination in Parent Material



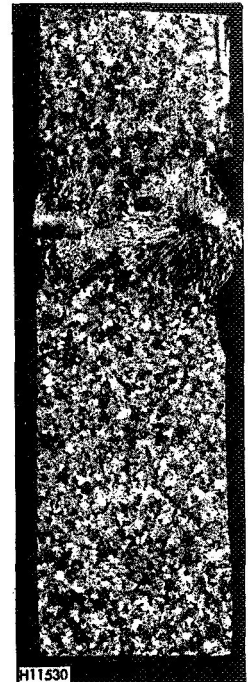
2X  
Sample from edge of 7075 plate alloy was melted in electric furnace,  
and sectioned longitudinally.



2X  
Cross section from  
same sample as above



Overhead 2X  
DCSP-TIG bead-on plate

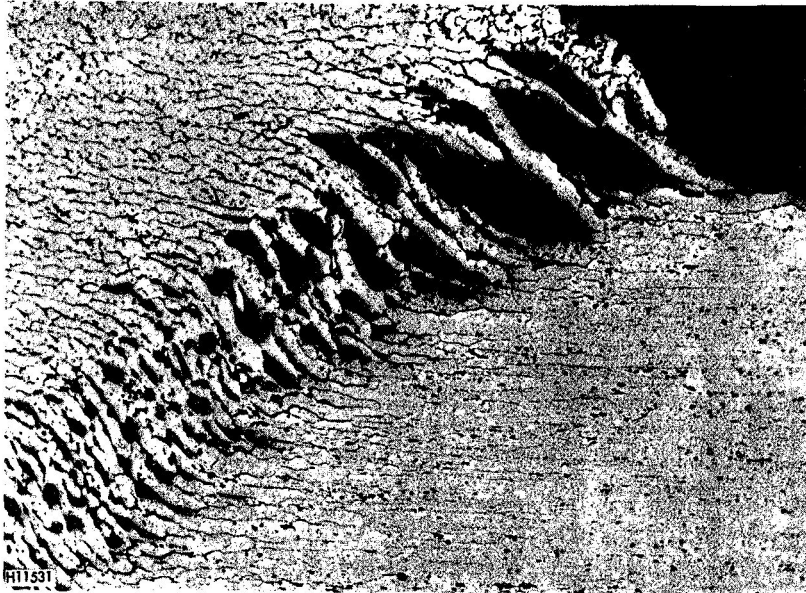


Horizontal 2X  
DCSP-TIG butt weld

Hot Caustic

Figure 16. Comparison of Porosity in Furnace-Melted Alloy 7075 and in Welded 7075 Plate

All of the above samples were made from the same parent material, indicating that porosity can be found by different means.



Phosphoric

50X

Figure 17. Gross Porosity in Heat-Affected Zone of Welded 7075 Alloy  
The heat of welding has apparently melted low-melting eutectic material, and at the same time expanded the hydrogen present, resulting in the spectacular separation shown in this sample.

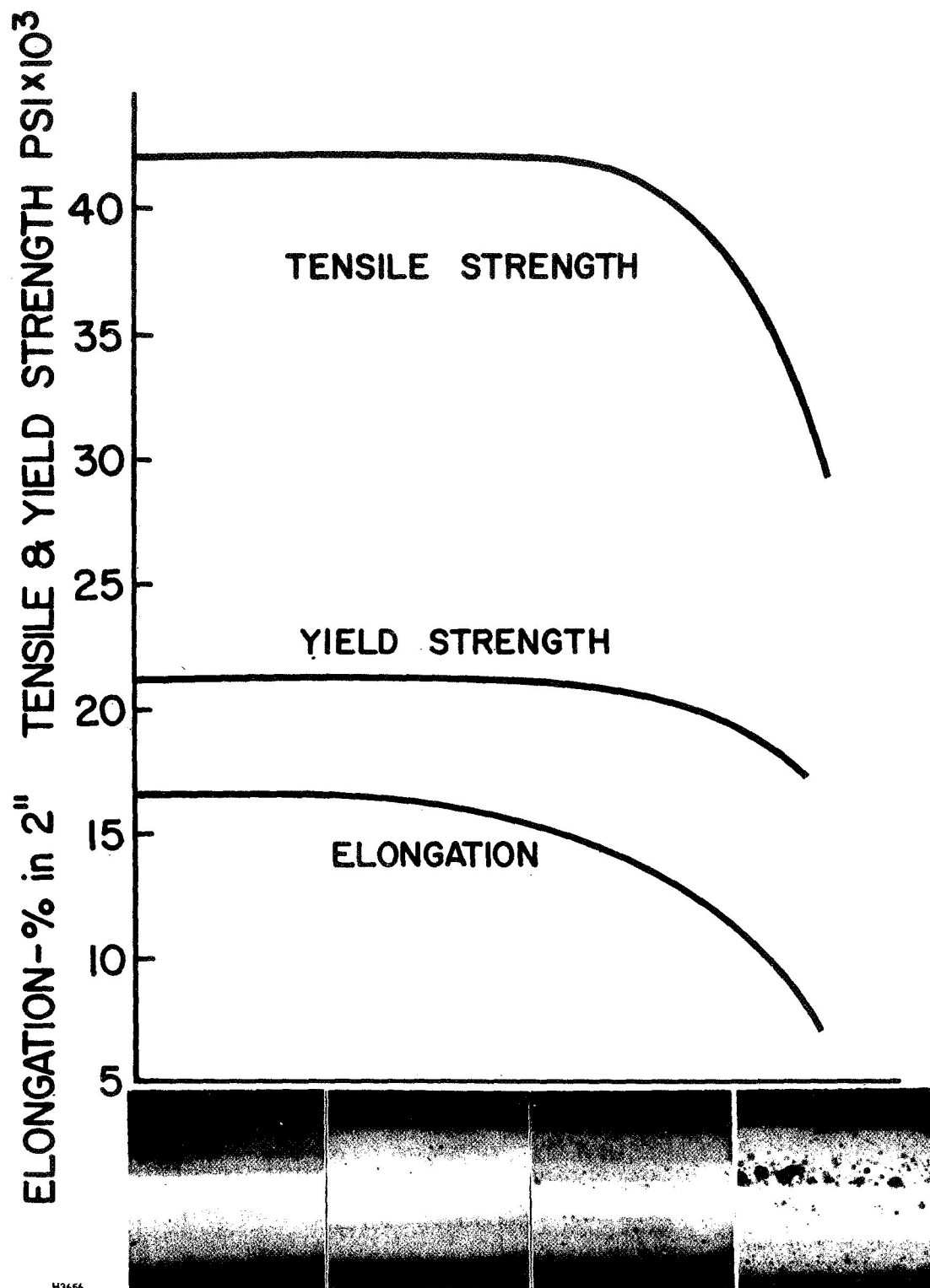


Figure 18. Effect of Weld Porosity on Static Tensile Properties of 5083-H113 Welded with 5356 Filler



## Dross

Dross is aluminum oxide or aluminum nitride films which may be generally scattered throughout weld beads. The presence of oxygen in the shielding gas or on the surface of the solidifying weld pool causes dross. Figure 3 shows the dross level obtained in a weld where 2.0 cu cm per min of oxygen was added to the shielding gas. In this case, the dross has the appearance of pepper on the fractured metal surface. Dross may also be present as a film in "cold shut" areas where the arc length has been too long and the weld bead has not been fused into the underlying metal.

## Poor Shielding

There are several sources from which oxygen can enter into the weld pool. The primary source is from poor shielding. Drafts in the welding area can cause a momentary or continual loss of shielding so that excessive air is allowed to contaminate the weld surface. If the gas flow is too low, inadequate shielding of the weld pool will result. It is believed possible that air entering the contact tube may be a factor in dross formation. Use of too small a gas cup for the diameter of wire, the current, and the size weld pool, can result in inefficient shielding and allow excessive air to get to the weld pool.

## Weld Wire Surface

The filler wire is another source of oxygen. If the wire has not been prepared in a manner which minimizes the thickness of the oxide film, the wire surface is a source of oxygen. Oxygen is also present in hydrocarbons which can be on the wire surface, particularly if the wire has been left open in the shop without protective plastic covers over the spools on the welding machines.

## Base Metal and Weld Oxide

Welding over base metal surfaces that have not been deoxidized or properly wire brushed prior to welding is another source of oxygen, particularly in sheet. Last, preceding weld beads are a source of oxygen if the beads have not been properly wire brushed before depositing the next succeeding bead. In joints which are to be welded from both sides, it is possible to have dross in the underside of root beads which may be removed by chipping, milling, or other means prior to depositing weld metal on the second side.

## Reducing Dross

Measures for reducing dross levels include shielding against drafts, using higher gas flows, pressurizing the contact tube with shielding gas, using larger gas cups. The possible introduction of oxygen from the weld wire can be minimized by using welding wire which has a minimum hydrated oxide film thickness and which is essentially free of hydrocarbon contaminants as packaged.

As aforementioned, a very simple check of the oxide film thickness on a welding wire can be made by melting welding wire samples in an oxyacetylene flame. Welding wires having a thin film can be differentiated from those having a heavy film by the nature and behavior of the molten droplet within the oxide bag which will form on the end of the wire being melted. Base materials should be cleaned and properly deoxidized or wire brushed prior to welding. Similarly, weld beads should be wire brushed between successive beads to reduce dross. Double-welded joints in many instances will require chipping or milling the underside bead to sound metal. In the case of high current density techniques, underside chipping is seldom necessary. Table II summarizes corrective measures for dross.

#### Effect on Mechanical Properties.

Dross has a serious effect on mechanical properties of the weld. Dross films act the same as microfissures or voids and result in a marked drop in tensile properties and ductility. Excessive dross in a weld preclude passing any kind of a bend test such as is required for procedure and operator qualification tests by ASME Section IX of Unfired Pressure Vessel Code.

Table II. Some Causes And Suggested Corrective Measures  
For Dross In MIG Weld Metal.

<u>Basic Cause</u>	<u>Contributing Factors</u>	<u>Suggested Corrective Measures</u>
Poor shielding	Drafts, causing loss of shielding. Gas flow too low. Entrained air down contact tube. Gas cup too small.	Provide adequate shielding against drafts in the welding area. Increase shielding gas flow rate. Pressurize contact tube with shielding gas. Use a larger gas cup.
Weld wire surface	Oxygen from excessive oxide. Oxygen from hydrocarbon contaminant.	Use wire with thin oxide film. Protect wire in shop with plastic covers.
Base metal surface	Heavy oxide film. Spatter particles.	Wire brush or chemically remove oxide. Adjust welding conditions so spatter does not occur ahead of weld pool.
Weld metal	Oxide film on preceding beads. Dross in underside of root passes.	Wire brush each bead before depositing next successive bead. Chip or mill underside to sound metal.

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## DISCUSSION

Mr. Rieppel: I have two questions, Frank. The first one refers to the flame test shown for the wire. In an oxyacetylene flame, you reach very close to the melting point, or you may even be at the melting point, when you're running that test. There is a good opportunity to pick up hydrogen from the products of combustion from the oxyacetylene flame. Does this in any way enter into the test?

Mr. Baysinger: That is a very valid criticism of the flame test, but we assume that the amount of moisture entering from the flame is a constant, and you can very definitely show variations between wires. These variations can be demonstrated to cause differences in the weld, and this is a test that we make many times for many people. It's a very reproducible thing.

Mr. Rieppel: The other question was concerning the use of chlorine as you mentioned toward the end of the talk. I have referred to this in my paper, and as a matter of fact, I said that this was about the only thing that I have found in the literature in the last few years that showed some means of getting rid of porosity other than the usual methods. The thing that I wondered about is this: if you run a little bit of chlorine down the guide tube, what is the mechanism of reducing porosity? Do you have any information about that?

Mr. Baysinger: There are two theories on this. I have my own and there's Vern Eastwood's. In Vern's theory, the reaction was first between the water and the magnesium or the aluminum, to form the oxide plus the hydrogen as shown in your equation. The chlorine then reacted with the free hydrogen to form hydrochloric acid, which then passed off with the shielding gas. That is probably the most correct. I have always looked at it this way because I also knew that oxygen works as a scavenger of the hydrogen, and I felt that perhaps it was more of an ionic action, and that the presence of the negative ions caused the free hydrogen that was formed, or the atomic hydrogen, to recombine before it hit the metal surface and passed off with the gas. It is quite probable that both mechanisms work, and who's to say? We can't tell. This, again, is an area that should be studied. I think that you could get more clues using the high speed camera, because these drops as they form, and particularly with the magnesium-containing and the zinc-containing aluminum, are very wild. They're not the typical teardrop shape that you normally see. They're like a bunch of mad spiders; they're real violent.

Mr. Saperstein: I think there might be another possibility too, Bob, that bears on your ionization idea, and that is if halogen, chlorine, oxygen, nitrogen, even helium, disassociates in the arc atmosphere, it changes the total concentration of ions in the arc atmosphere. And this alone, changing the concentration of ions, can inhibit a reaction, progressing in one direction or another. This may be a factor. I don't know.

Mr. Hutchinson: I am in quality control. Are you suggesting that these be acceptance tests at a manufacturer's plant?

Mr. Baysinger: It could come to this. Right now, I don't think that you could get any supplier to agree to the test. This will come in time, and ultimately such testing will be done the same as the MIL specification for low hydrogen electrodes. There the hydrogen quantity is spelled out, and the method of measuring it is spelled out. I would say that it would be five years before there is actually a MIL specification which covers these features; however, while you are waiting for that, there is sure nothing wrong with looking at your materials that you are going to use for radiographic quality weld. You have the power of inspecting it right now.

Mr. Hutchinson: Well, if we did this, how much usable wire do you think we would get?

Mr. Baysinger: This is a problem that I'm faced with every day in working with pressure vessel fabricators whose standard of radiographic quality is in no way different than the NASA Class 2 standard. These people work under field conditions with high winds, drafts, poorly trained, locally procured operators---every problem in the book---and have to meet a NASA Class 2 standard, and they do it. But they do it by checking their materials and just making sure that they do not get a bad wire. They put up draft shields, properly wire brush, and they make the welds. As to how much wire is rejectable, it's possible to reject 50 percent of it; but remember, that half of it is good.

Mr. Chyle: I'd like to comment; is it true that in the making of these aluminum alloys, that sometimes they use chlorine in the refining of aluminum when they make these ingots for rolling?

Mr. Baysinger: Yes, that is a standard practice. Because, remember in the aluminum industry, we have been producing metal for the aircraft industry for years; and "defect" to the aircraft industry is something like a 64th of an inch in diameter. A "defect" in the steel industry is something you can put the head of a match in. So, we're used to producing a much higher quality material to begin with. The problem is not due to the fact that we're not doing these things, but as Gus pointed out, we don't know what to degas to. The level has not been determined--the relationship to the amount of gas we can tolerate in the metal versus the weld. So, chlorine is used. I think this is universal in the industry.

Mr. Chyle: Your first chart also showed that there was a relationship with the time of day, the humidity, and the various months of the year. I wonder if you would comment on that. It seemed that the next picture was four or five X-rays, or did it precede with increasing amounts of porosity? Now how was that correlated? Can you tell me?

Mr. Baysinger: Yes, that slide was to show one thing: if your relative humidity, or whatever this is in terms of absolute humidity, is below 50 percent; your wires can be stored for indefinite periods of time without any appreciable practical degradation. If the humidity goes over this point though, your wires begin to deteriorate, and probably a month storage time is all you can tolerate without being in a dry room. This work led to the universal packaging that is now used, putting the wire in some kind of vapor-barrier package. The only problem is who's to say that what went in there is perfect. We're leaving something out here somewhere.

Mr. Chyle: I might pass this on. I, myself, had this experience. I had a wire that did produce porosity in MIG welding. I took that wire in coil form and heated it in an electric oven up to about 250-300°F for about 3 hours, and after that I used the same wire. The porosity was almost gone. It might have had a direct effect on heating up this wire that apparently had been contaminated. I wonder if someone has had a similar experience like that. Preheating this bad wire did give us relief. Now, it wasn't 100 per cent, but it was good enough that we could use it. Yes, Mr. Brown?

Mr. Brown: In the foundry industry, this is an old trick of preheating the ingot which we suspect has been exposed to ambient conditions--- (inaudible)---. And, of course, Mr. Baysinger pointed out that preheating to avoid the chill in the first pass is most effective. Also, I understand that in many cases, those people that do a lot of aluminum welding use copper chills. They preheat the copper chills, again in the range of 150-200 degrees, to get rid of this root porosity.

Question: Speaking only of MIG welding, I would like to know if you have found any difference in the porosity level between the conventional full spray transfer arc and the so-called short circuiting arc?

Mr. Baysinger: The short-circuiting arc gives you an inherently high cooling rate and that alone causes you difficulty. So, the procedures which you must use to eliminate porosity are at the other end of the scale. If you could always make your welds in one inch plate, for example, single pass high current density welds, you'd never see porosity. You could take mill run wire, undegreased, unshaved, just a produced-fence wire and make a perfect weld with it. We have done this.

Question: Can I assume then, that you're saying that to get a water clear negative, you should not use the short circuiting process?

Mr. Baysinger: Not unless you have absolutely perfect materials. It can be done. But, you are multiplying the problem; everything is against you. You have no margin of reserve.

Mr. Chyle: I think we will have to close this very interesting discussion, and again, we want to thank Mr. Baysinger for a very, very fine presentation.

TIME-TEMPERATURE EFFECTS IN WELDING  
2219-T87 ALUMINUM ALLOY

By

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## INTRODUCTION

In the welding of any material, it is essential that limits be established for material, welding process, and tooling before component designs can be realistically formulated. The data to be presented to you now are just a beginning of such limit definition. There are many areas yet to be investigated, and needless to say, the conclusions are tentative, needing further validation.

Generally, a definite trend or pattern of test results has been observed and a direction for further testing is clear. As we gather basic, reliable, background data, further testing becomes more meaningful and less voluminous.

Our study deals with 2219-T87 aluminum alloy plate in thicknesses from .224 inch to 1 inch. Both TIG and MIG processes are used with one pass and two passes from one side, and two pass, one from each side welding. The welds were made in the horizontal position, using square butt joints, and in the free state with no backup or hold down tooling. Evaluation is based on tensile properties, X-ray quality, energy input versus tensile properties, metallographic analysis, and process limits and control.

### The Effect of Time-Temperature on Tensile Properties

Fusion welding is basically a temperature-time process with a heat source moving in relation to the material. The effect of time at temperature during welding on tensile properties of welded 2219 is the primary issue of this study.

Figure 1 shows the relation of heat energy input to ultimate tensile strength. As heat input is increased strength is sharply decreased, up to a point; then strength reduction is gradually lowered. Even though data for this plot were taken from several different programs a definite pattern is established as indicated within the limits of the banded area. Under controlled test conditions employing the same welding equipment, heat energy and tensile data have demonstrated a closer correlation.

In order to provide a common denominator for all thicknesses, heat input was calculated on the basis of joules per inch divided by thickness of the work piece. Furthermore, data were found to correlate better when using only the heat input of the fusion pass of a two pass one each side weld.

The fact that welding two pass, one from each side provides greater strength than single pass or two pass one side suggests that there is a second major factor influencing the time-temperature ratio in addition to weld heat input; that is melt area to heat sink. When TIG welding with partial penetration, the resulting melt area is normally smaller than the area required for complete penetration. Thus, in a two pass one each side weld, the combined time-temperature effects for both passes on strength reduction is lessened. The same phenomenon is seen when welding with MIG.

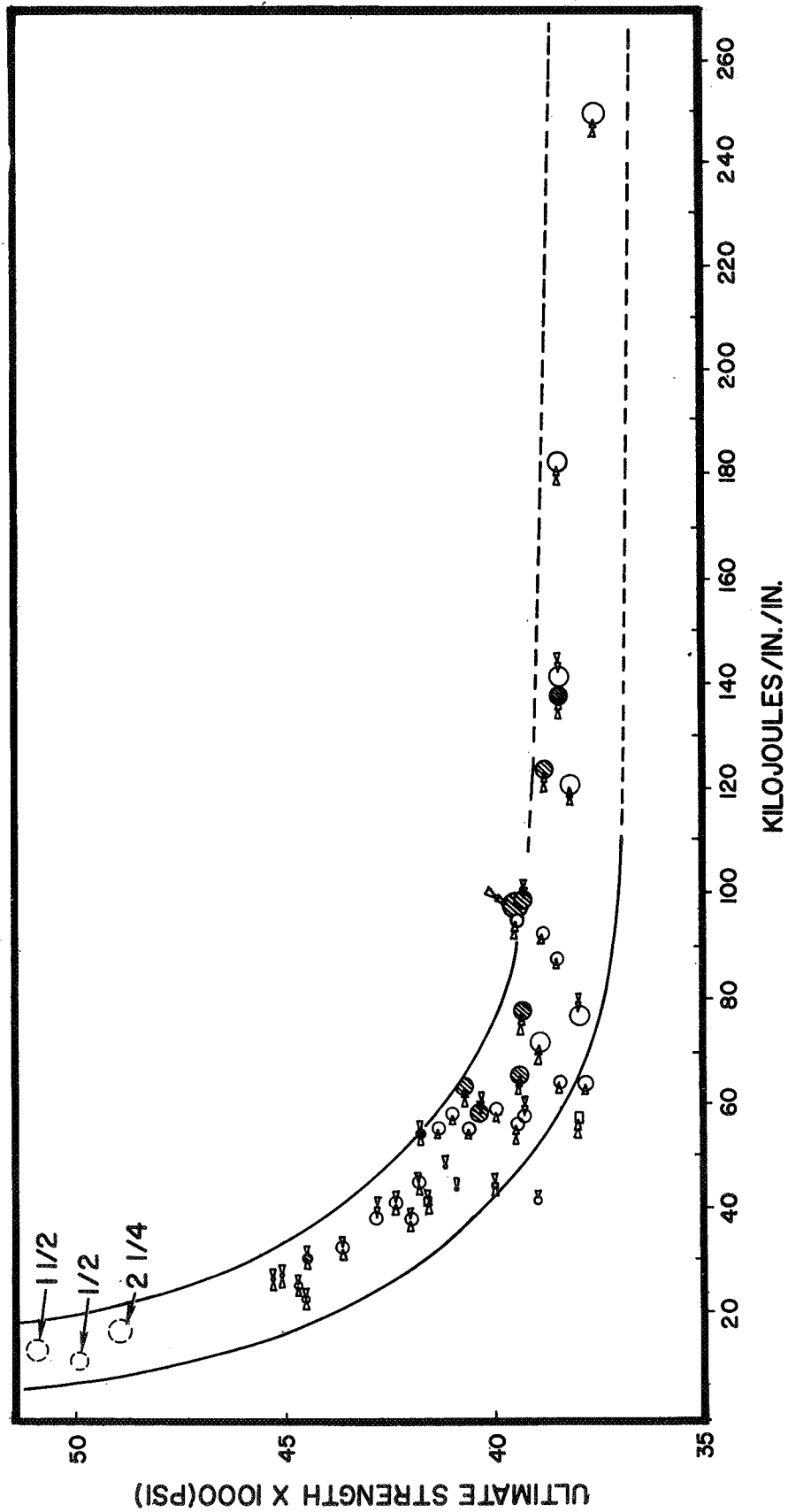


Figure 1. Relation of Weld Heat Input to Ultimate Strength 2219-T87 and -T87 TIG, MIG, and Electron Beams. .224 to 2 1/4 Inch Thicknesses

The MIG process has been noted to produce a larger melt zone. Thus, with the same heat sink capabilities for both processes, it follows that the time-temperature effect would reduce strength more with MIG than with TIG.

Although a definite trend is indicated, contradictory data do exist. Some tests are being repeated for validation. Additionally, a confidence level must be established for the data scatter band. There are many factors besides energy input which will cause variation in tensile strength. These must be isolated and analyzed either by simplified tests or by quantitative data analysis. An indicative list of such factors includes filler metal, bead shape, quench rate, parent metal strength, mechanical notches, strain rate in tensile tests, even such details as micrometer measurement of specimens. Only after these factors are considered can the sensitivity of the material to energy input variation be accurately established.

### Metallographic Analysis

Aluminum alloy 2219 is basically a binary eutectic system of Al-Cu, and thus is heat treatable. In the solution heat treated and artificially aged tempers, the mechanical properties of 2219 may be reduced by a maximum of only five percent by reheating to a temperature of 500°F. Therefore, it is reasonable to assume that the major loss in strength caused by the heat of fusion welding will be limited to the zone which was heated above 500°F.

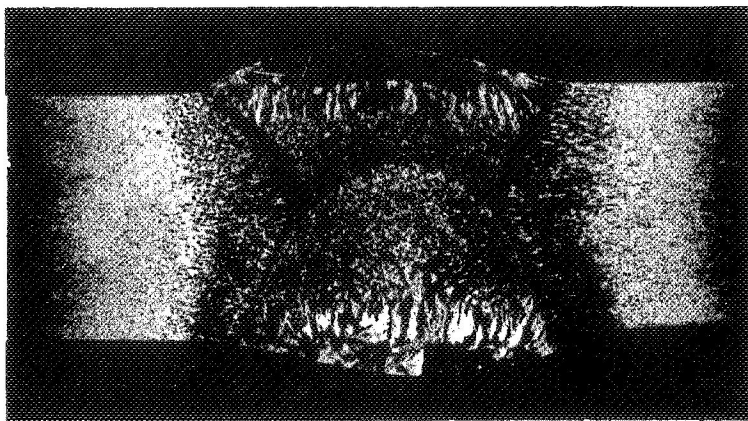
The reduction in mechanical properties of this alloy by welding is primarily due to the time at temperature above 1000°F which results in eutectic melting. Evidence of this melting is observed in the microstructure in the form of widened grain boundaries and eutectic melted and agglomerated brittle phases, principally CuAl<sub>2</sub>. The amount of grain boundary eutectic which forms is a function of time at temperatures above 1000°F attained during welding. In this investigation the time at temperature was controlled by varying the welding speed.

Figure 2 shows photomicrographs of welds made at 10, 30 and 60 ipm which have been chosen to illustrate the effect of unit heat input on macro-structure and microstructure.

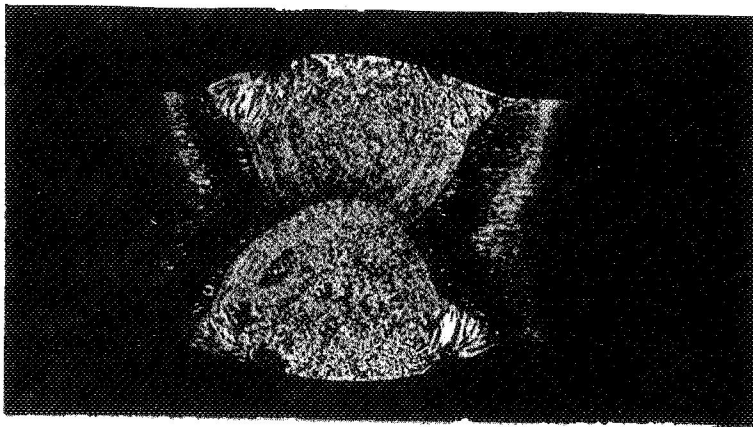
The welds made at 30 ipm and 60 ipm have much shallower weld beads, narrower apparent heat-affected zones, and finer cast metal grain sizes, all of which indicate less total unit heat input and faster cooling rate. The welds made at 30 and 60 ipm have approximately the same bead width; however, the 60 ipm weld has less penetration and a finer cast metal grain size.

Figure 3 shows the cast metal/heat-affected zone interface of the three respective welds. The weld made at 10 ipm has a much wider transition zone with considerably more agglomerated CuAl<sub>2</sub>.

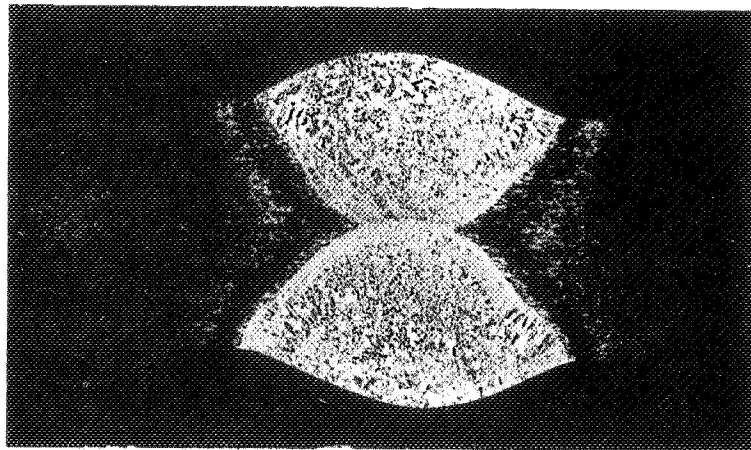
Figure 4 shows the same areas at higher magnification. The 10 ipm weld has an almost continuous network of CuAl<sub>2</sub> at the grain boundaries. The welds made at higher speeds and therefore with lower energy input shows progressively less CuAl<sub>2</sub> at the grain boundaries. These welds also show less agglomerated CuAl<sub>2</sub> particles within the grains.



a. 10 IPM



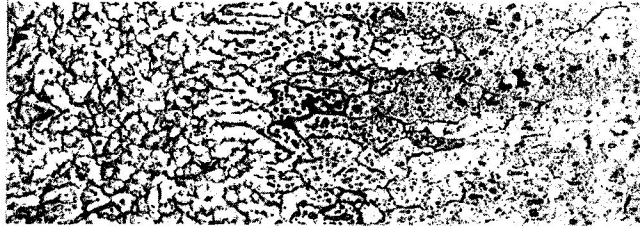
b. 30 IPM



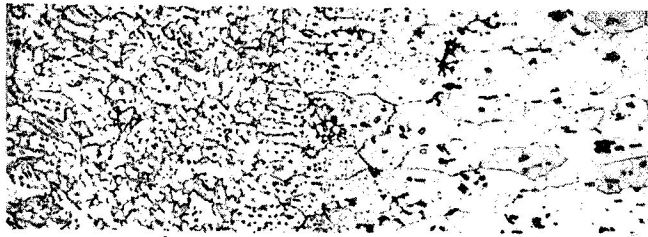
c. 60 IPM

Figure 2. Micrograph of 2 Pass Weld, One Pass Each Side at 7X

a. 10 IPM



b. 30 IPM



c. 60 IPM

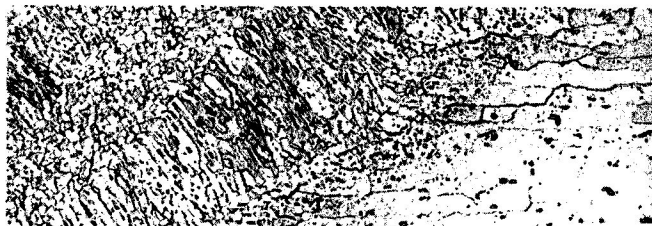
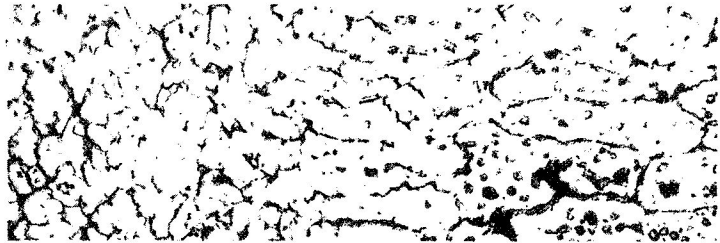
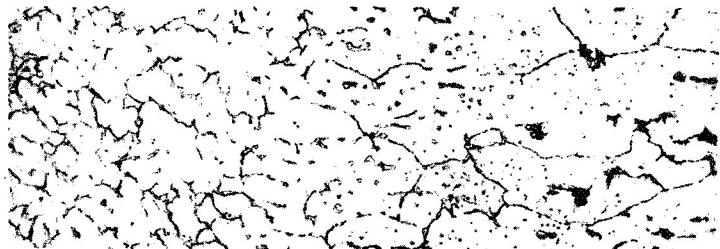


Figure 3. Micrographs of 2 Pass Weld, One Pass Each Side at 200X

a. 10 IPM



b. 30 IPM



c. 60 IPM



Figure 4. Micrographs of 2 Pass Weld, One Pass Each Side at 500X

## The Effect of Time-Temperature on Porosity Size and Count

We reason, from experimental data, that frequency, location, and size of porosity can be correlated with time-temperature. Results of welds made on 132 inch diameter cylinders appears to indicate this to be so. Data from these welds are plotted in Figures 5, 6 and 7.

Figure 5 shows 375 inches of one weld, representing a low heat input of 33,000 J/in./in., required a repair rate of 1 percent.

In Figure 6 the graph indicates that as welding speed is increased with correspondingly less energy input, the porosity level drops, and the porosity location moves toward the center of the nugget, suggesting that porosity is being inhibited in its formation.

The location of the porosity can be a basis for reducing the number of repairs. If the porosity lies within the center portion of the weld, it will have less effect on joint strength. If located at the interface between the weld it may initiate tensile failure.

At some level of reduced time-temperature, the formation of porosity should be almost entirely prevented, or at least controlled to be so finely dispersed that it would not be discernable. This fact has been revealed by high speed electron beam weld evaluation.

Figure 6 shows the porosity level at three travel speeds. At 30 ipm, 1 percent repair was required, similar to the 359 inch weld. This shows that speeds 25 ipm and above result in a marked reduction in porosity level in this .224 inch material thickness. The technique of welding should be oriented toward these higher travel speeds or toward other means of reducing time-temperature.

Figure 7 shows the correlation holds with .224 inch thick cylinders welded by the MIG-DCRP process. Note the extreme drop in porosity level as travel speed is increased from 25 ipm to 35 ipm. At 35 ipm, 0 percent repair is required. However, in comparison with the TIG process, tensile properties are consistently lower.

## Process Control and Limits

Many combinations of amperage, voltage, and travel speed were tried. The results in mechanical properties related to energy input were logical; however, some of the process combinations are not practical on a production basis. Penetration control related to travel speed is probably the most critical area. At a fast travel speed, the process approaches the minimum energy input necessary to penetrate the material. The non-uniformities, such as plate offset, thickness changes, tooling slots, changing heat sinks, material movement, etc., become most influential. Also, the time for response required from equipment and operator decreases, whereas the equipment and human response mechanisms remain constant.

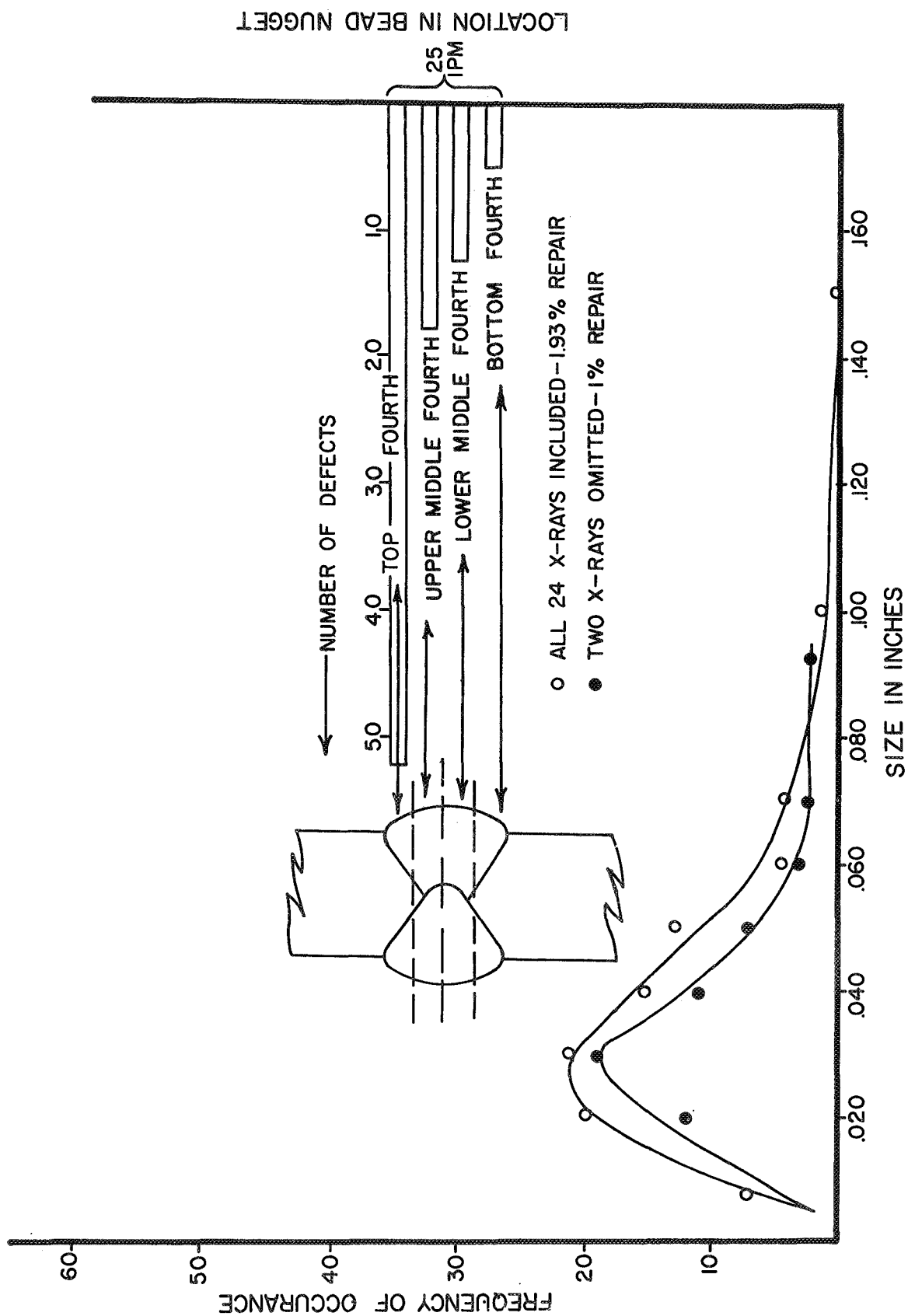


Figure 5. Defect Size Vs. Frequency-.359 Inch -2 Pass Opposite Side-TIG



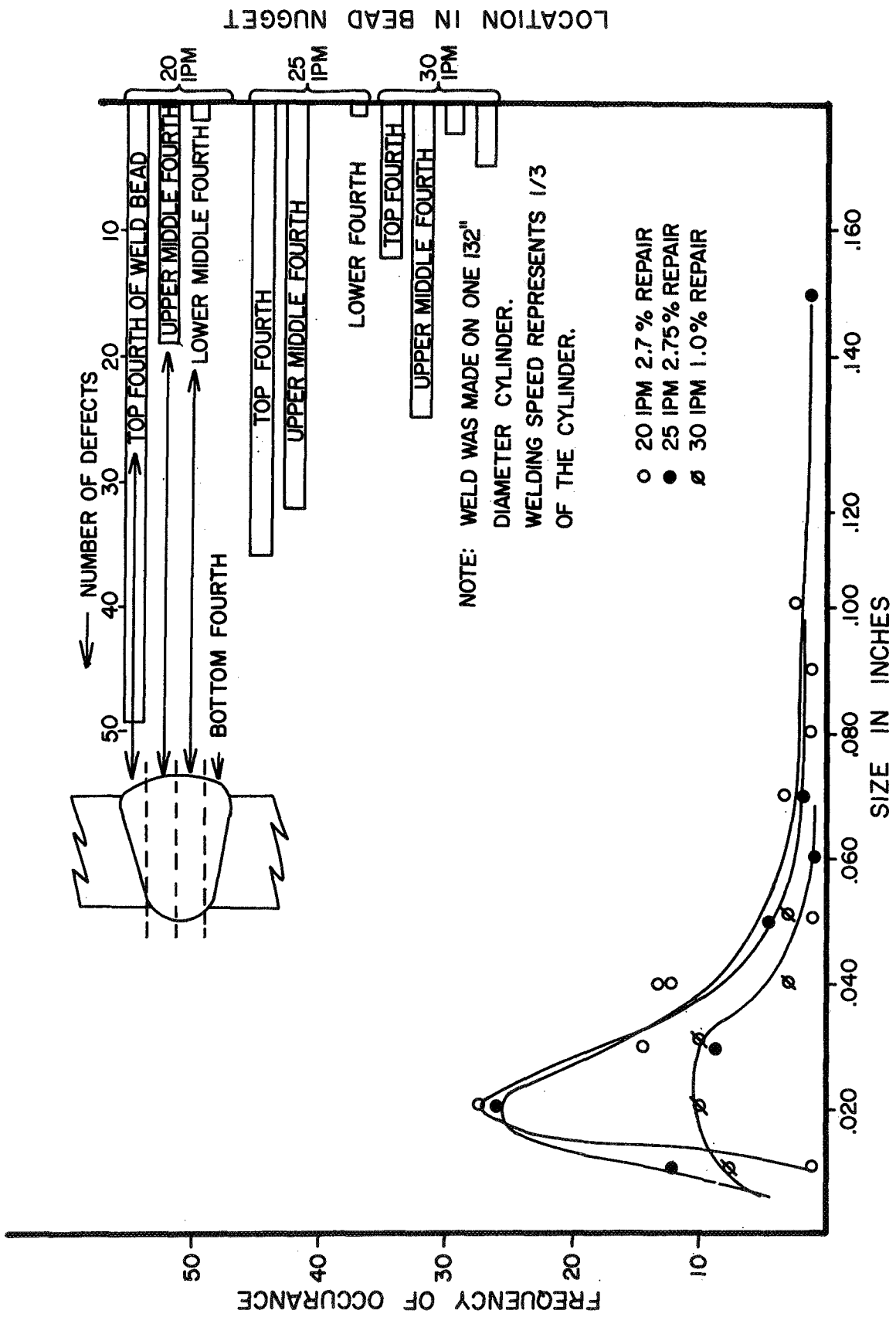


Figure 6. Defect Size Vs. Frequency-.224 Inch Thick TIG-One Pass

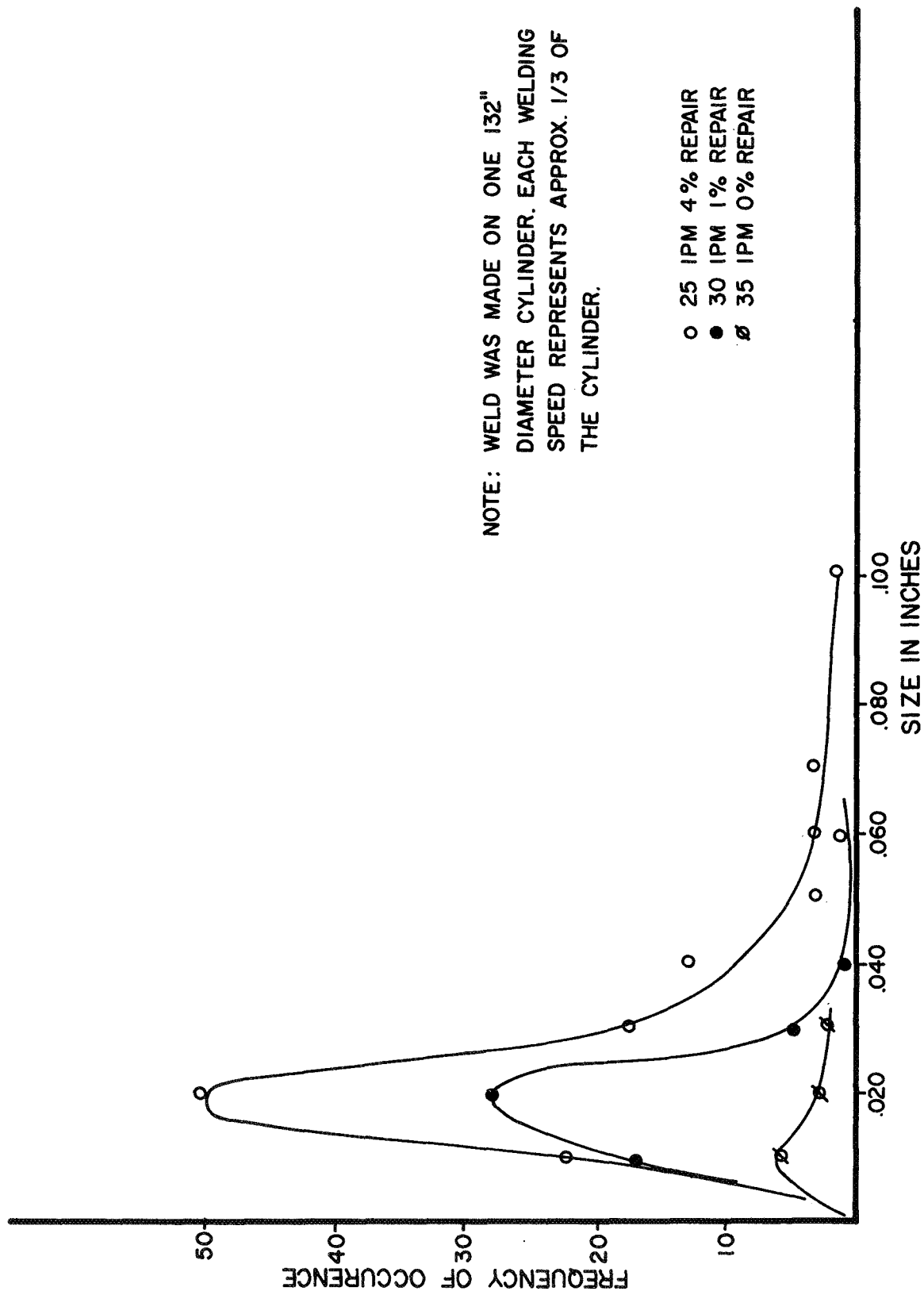


Figure 7. Defect Size Vs. Frequency-.224 Inch MIG Weld-Single Pass

The translation of laboratory controlled data, such as machine settings; etc., to the production level must be done on a practical basis. Penetration control, time for operator response, plate offset, and so on, are necessary considerations. These must be carefully studied and included in the confidence level.

#### SUMMARY

The following trend conclusions can be made: An energy input of 45,000 to 240,000 joules in all thicknesses gives 38,000 to 41,000 psi ultimate tensile strength in weld joints. As the energy level is further reduced, the strength sharply rises; TIG welds at 22,000 joules/in./in. developed 45,000 psi and electron beam welds at 12,000 joules have developed physical properties 15 percent to 20 percent higher. Porosity size and count decrease as time-temperature is lowered.

#### FUTURE OBJECTIVE

The objective, then, has become "control of time-temperature ratio". Amperage, travel speed, mass, external chilling, etc. are variables which can be manipulated to produce the desired time-temperature ratio. The point is, control that ratio, even if you have to throw water on the weld.

## DISCUSSION

Mr. Hackman: I would just like to say that much of what you have outlined there correlates with our own work, particularly the movement of the porosity downward with the increase in speed, which I think confirms what we all have felt, that the porosity in the top edge of the three o'clock weld was strictly a case of gravity. If we gave it enough time, it very nicely moved or bubbled to the top edge. If we welded fast enough -- although the hydrogen was probably, whatever the source, dispensed around there --- we didn't give it a chance to move up to the top. I'm curious along this line. When you found this porosity had moved down, was it closer to the surface of the weld as compared to where the porosity lay at the top edge of the weld?

Mr. Case: In this thickness, it is difficult, even with 45° techniques, to determine the position of porosity within the weld itself. I was merely counting the frequency of it. Some welds that we have cross sectioned indicate that the porosity is from the middle out; in other words, it is not in the outside layer and it is not in the bead reinforcement. You can't just come along and shave it off, unfortunately. Does that answer the question?

Mr. Chyle: I believe there is a question here.

Mr. Saperstein: There is one question that that comes to me, Mr. Case. Where you generated porosity, were the other conditions aside from their thermal variables measured and known? What do you believe to be the cause of porosity, that is, what was the source of hydrogen? Another comment is that perhaps the entrapment of porosity near the root section of the weld at the higher travel speeds is, in part, due to the shape of the solidification of ripple zone volume. At high travel speeds, this wave front takes the shape of a very elongated shovel-like geometry, and it is difficult for the pores at the bottom of the root where you have this elongated shovel, to get out of this ripple zone. They have a more difficult time migrating upward through the zone.

Mr. Case: We tried without success to vary the attack angle to see if this could be controlled in the ripple zone, as you say. We had no real luck with it. I think it would be very difficult for me to say what caused the porosity. I was not attacking it from this standpoint. We were using our standard welding and cleaning techniques, trying to see if we could eliminate porosity by speed or some method of controlling time and temperature.

Mr. Bandelin: I have one thing to say that I didn't hear you comment on. In automatic TIG welding of horizontal 2219 material, you didn't mention the location of the filler wire in relationship to tungsten. In running many of the horizontal tests, I found we can eliminate an awful lot of this "upper porosity," as you referred to in your slides, by the location of the filler wire in relationship to the top; thereby, putting a larger quantity of molten mass and equalizing the mass rather than have the gravity let it droop down. Solidification was faster on the top than for the rest of the mass. This gets away from a lot of the porosity that you're trying to evaluate.

Mr. Case: In this study, we introduced the wire from the front of the puddle, the top of the puddle, and the bottom of the puddle; also, from the back of the puddle in the same relationship. We didn't see much change, whether it was front or back. It was at the top portion of the weld where the wire was introduced.

Mr. Faulkner: I was very interested in the repair rate that you have there. I was wondering if you could review what you call your standard cleaning procedures for the plate, and also the control you maintained on the dewpoint of gas during the welding program?

Mr. Case: I will answer on dewpoint of the gas. We tried to maintain the gas below a minus 65°. This is for both the tacking gas and the gas for the predominant weld, which is put in by an automatic welder. Most of the welds at Marshall, due to the size of the vehicle, have to be cleaned by scraping. We do this with a triangular, sharp, scraping. The area to be welded is scraped to a depth of approximately .005 of an inch on each side of the three surfaces and extend about an inch away from the surfaces to be joined. We have not, in this work, gone into chemical cleaning for welding. It is a little impractical to put these big vehicles in a tank.

Mr. Chyle: Mr. Case, am I right in assuming that these defects are all porosity defects? Is that true?

Mr. Case: This is true. In this alloy, to date, except for puddle cracks which occasionally occur, I have not discovered cracking.

Mr. Chyle: Again, in the interest of saving time, I wish to thank Mr. Case for this very well prepared and informative paper.

AN ANALYSIS OF HEAT TRANSFER.  
DURING THE WELDING OF  
2219-T87 ALUMINUM ALLOY PLATE

By

Cecil L. Cline

LOCKHEED MISSILES AND SPACE COMPANY  
SUNNYVALE, CALIFORNIA

## INTRODUCTION

The Large Space Vehicle Programs of LMSC, Sunnyvale, is privileged to conduct a series of aluminum welding investigations for the Materials Division of R-P & VE. We in the welding field are well aware of the significance of heat transfer during the welding of heat treatable aluminum alloys, and the resulting degradation of engineering properties. The investigation to be discussed today was formulated to determine and analyze the influence of the major welding variables on the heat transfer characteristics of 2219-T87 aluminum alloy plate.

This investigation, directed by LSVP Engineering, analyzes the effect of travel speed, amperage, plate width, backing geometry, backing mass, and clamping pressure on the heat transfer characteristics. The program is currently in work and this presentation includes the results to date. A final engineering report will be prepared and copies will be transmitted to MSFC following completion of the program.

### Test Procedure - General

The welding program is being conducted with a Sciaky Zero Error power supply utilizing the direct current-straight polarity gas tungsten arc process. The test plates are 3/8 inch 2219-T87 aluminum alloy. The welds are vertical bead-through-plate located on the plate centerline. The temperature of the plates is obtained by temperature sensitive lacquer (300°F, 500°F and 700°F) and an array of thermocouples in conjunction with a multi-channel recorder. The welding parameters are monitored by an 8 channel Brush recorder. The program is being conducted in two separate phases: Phase I without supplementary cooling, and Phase II with backing tools of varying design.

### Phase I Procedure

This phase of the program utilizes plate widths of 7½, 15 and 22½ inches (20t, 40t and 60t) at travel speeds of 4, 6 and 8 inches per minute. The plates are held in the vertical position at each end to eliminate heat transfer to associated tooling. The test setup and concomitant recording equipment are shown in Figure 1. The temperature sensitive lacquers are applied to the root side, adjacent to the thermocouple array, as shown in Figure 2. Color motion pictures are obtained of the lacquers during welding.

The welding parameters are maintained constant, except current, which is 191 amperes at 4 ipm travel, 212 amperes at 6 ipm, and 232 amperes at 8 ipm. The wire feed rate is 4 inches of wire per inch of weld travel speed. After welding the test plates, measurements are taken to obtain the distance from the weld centerline at which the lacquers melted. The temperature data obtained from the lacquers are correlated with the data from the thermocouple recordings.

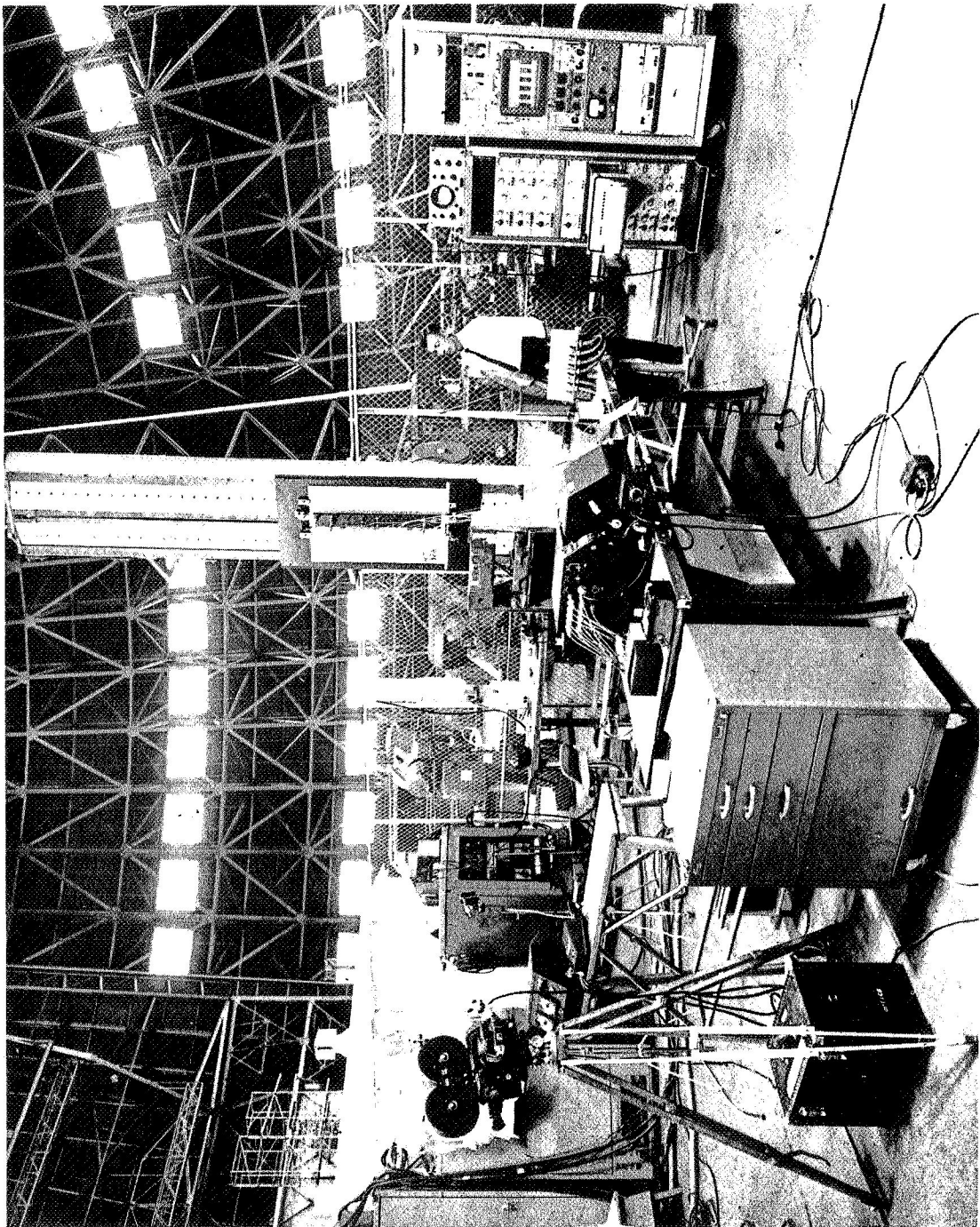


Figure 1. View of the Welding Area and Associated Instrumentation



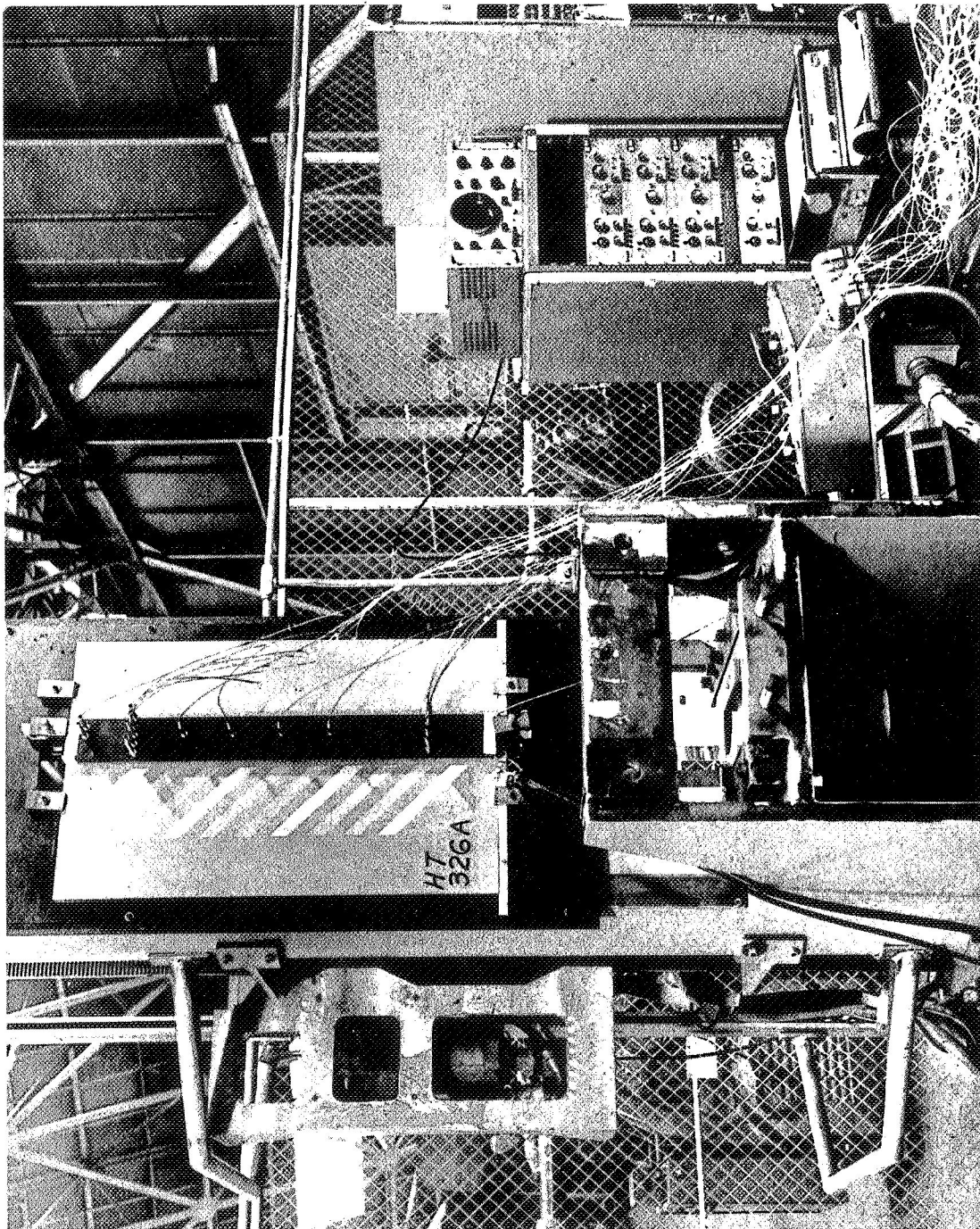


Figure 2. Test Setup Showing Temperature-Sensitive Lacquer and Thermocouple Mounting

## Phase I Results

The influence of plate width and travel speed on the heat transfer characteristics is shown graphically in Figures 3 and 4. This data demonstrates that the higher temperatures are not significantly influenced by travel speed on the wider plates. The macro-hardness values, as influenced by travel speed, are shown in Figure 5. The data were obtained from the 15 inch and 22½ inch plates, and disclosed, as expected, that the hardness values did not vary on these two plate widths. The extent of property degradation, as determined by hardness, is significantly influenced by travel speed. Mechanical testing of tensile specimens from the 15 inch and 22½ inch plates welded at the three travel speeds revealed the following:

Avg ultimate	39,050	Range	38,500 - 40,300 psi
Avg yield	20,900	Range	20,200 - 22,100 psi
Percent Elong. (2 inch)	6.1	Range	5.0 - 7.0

The 15 and 22½ inch wide plates exhibited a uniform bead profile at all travel speeds, while the 7½ inch plates were characterized by excessive root bead width at all travel speeds, indicative of high welding current. The results also demonstrated that the welding current is linear with respect to travel speed in the absence of supplemental cooling.

## Phase II Procedure

The welding for Phase II is limited to two travel speeds (4 & 8 ipm) and two plate widths, 7½ and 15 inches. The weld tooling utilizes copper hold downs with 304 CRES and with high conductivity copper backing. (See Figure 6.) The backing bars are fabricated with adjustable geometry, permitting a change in mass (3/8 x 1 and 3/4 x 1) and spacing (3/8 and 3/4). The effect of hold down shoe pressure, at constant shoe spacing of 1-1/16, was determined at 30 and 60 psig.

The temperature sensitive lacquer is applied to the face side of the plates, behind the hold down shoes to eliminate any influence on heat transfer to the shoes. The backing bars are drilled to permit the mounting of the contact thermocouples at specified intervals from the weld centerline. Weld procedures were established for each travel speed, tooling material, and tooling geometry. Arc voltage, gas flow rate and the wire feed travel speed ratio were maintained constant. The weld procedure objective was uniformity of weld bead profile under all welding conditions.

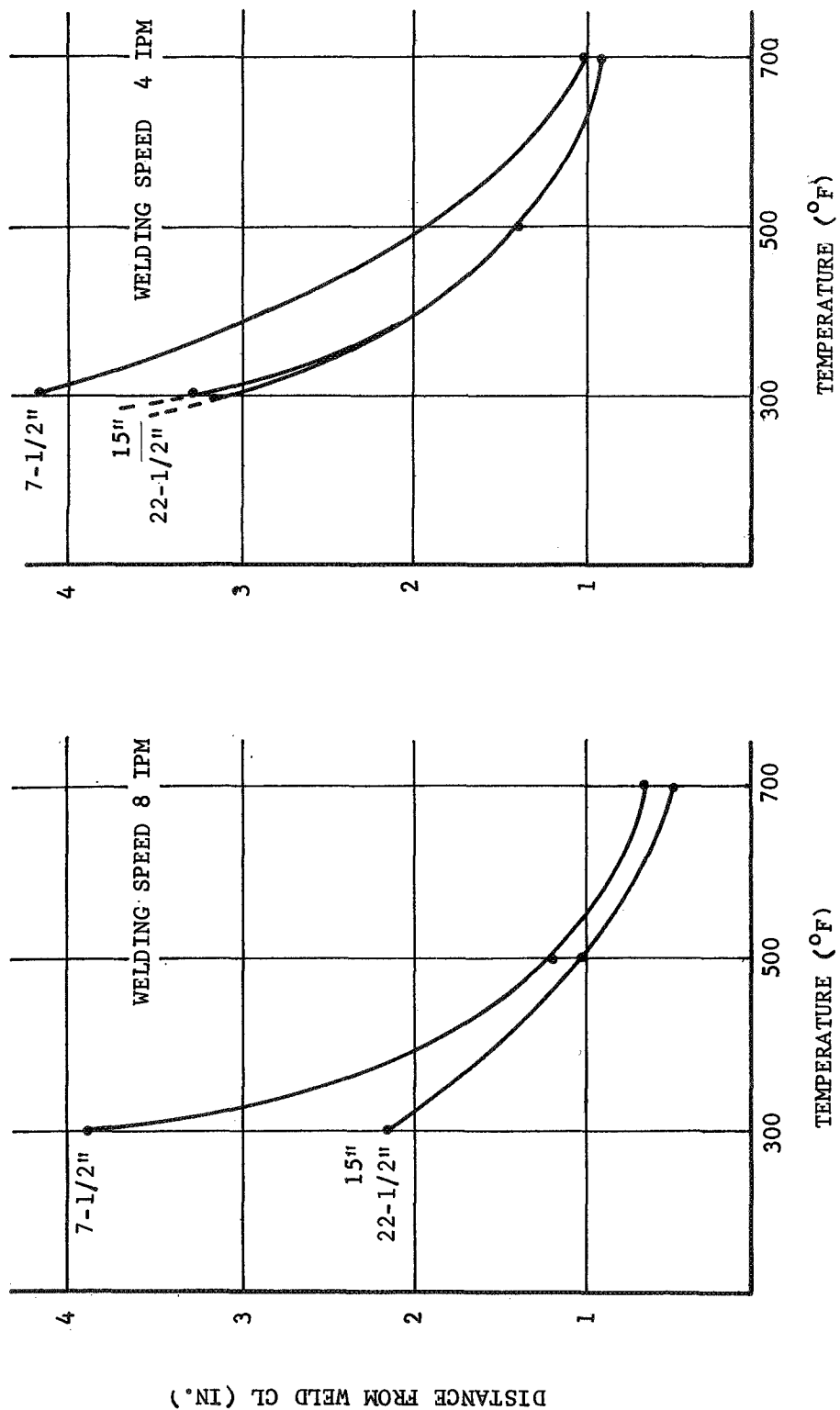


Figure 3. Influence of Plate Width on Heat Transfer Characteristics at Two Welding Speeds

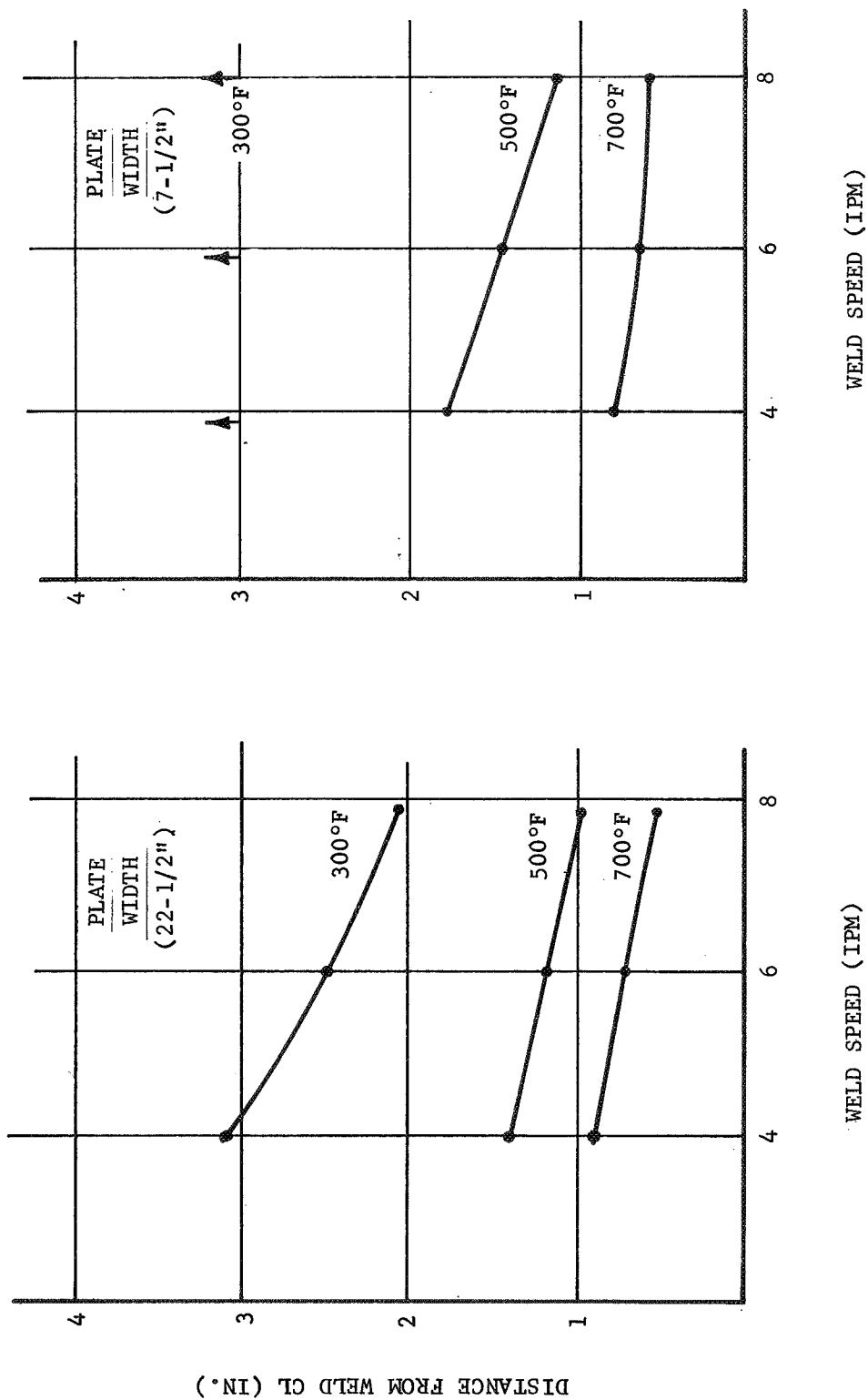


Figure 4. Influence of Welding Speed on Heat Transfer Profiles of Two Plate Widths

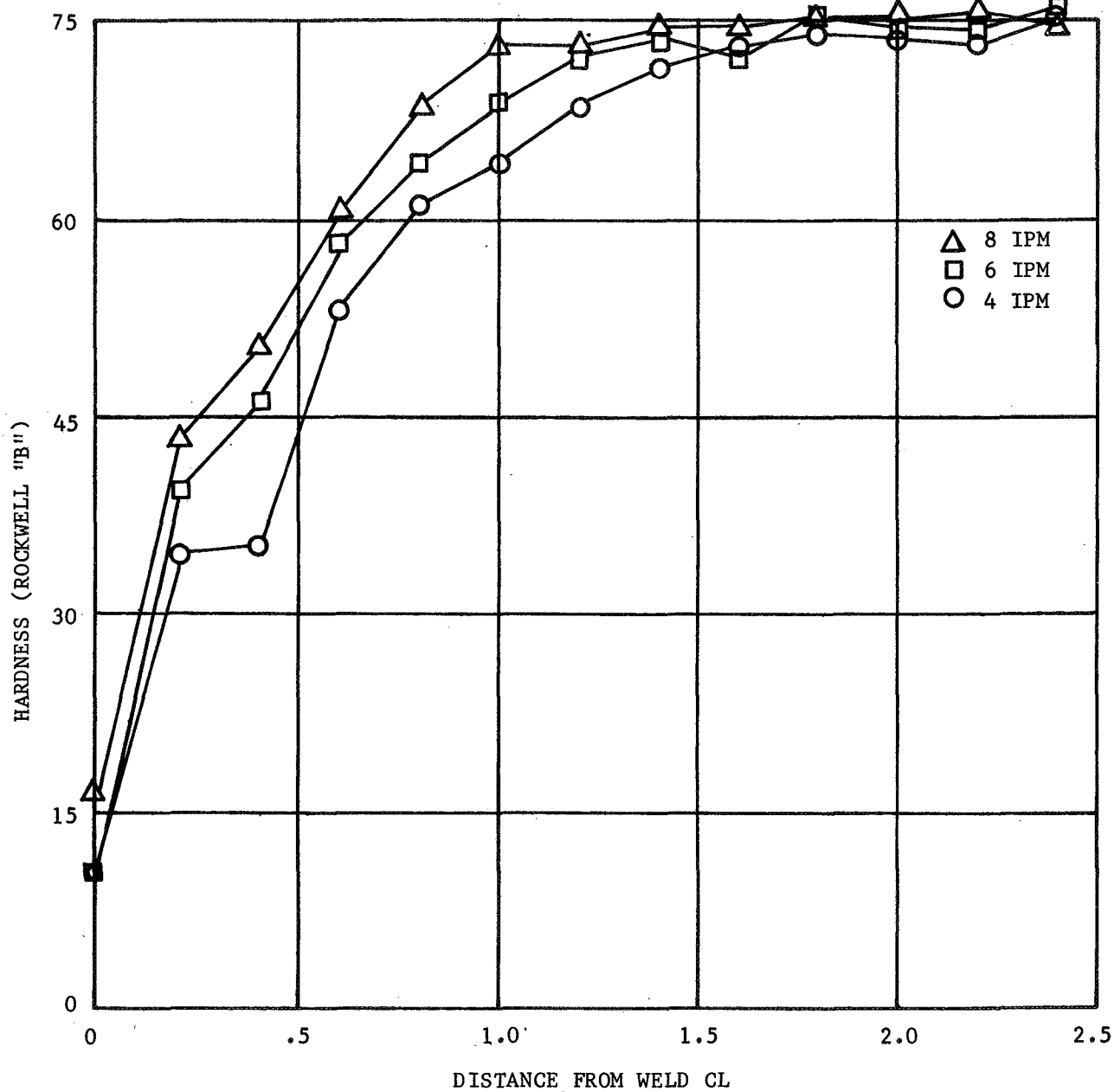


Figure 5. Average Hardness of the Weld and Heat Affected Zone as a Function of Travel Speed, Without Backing

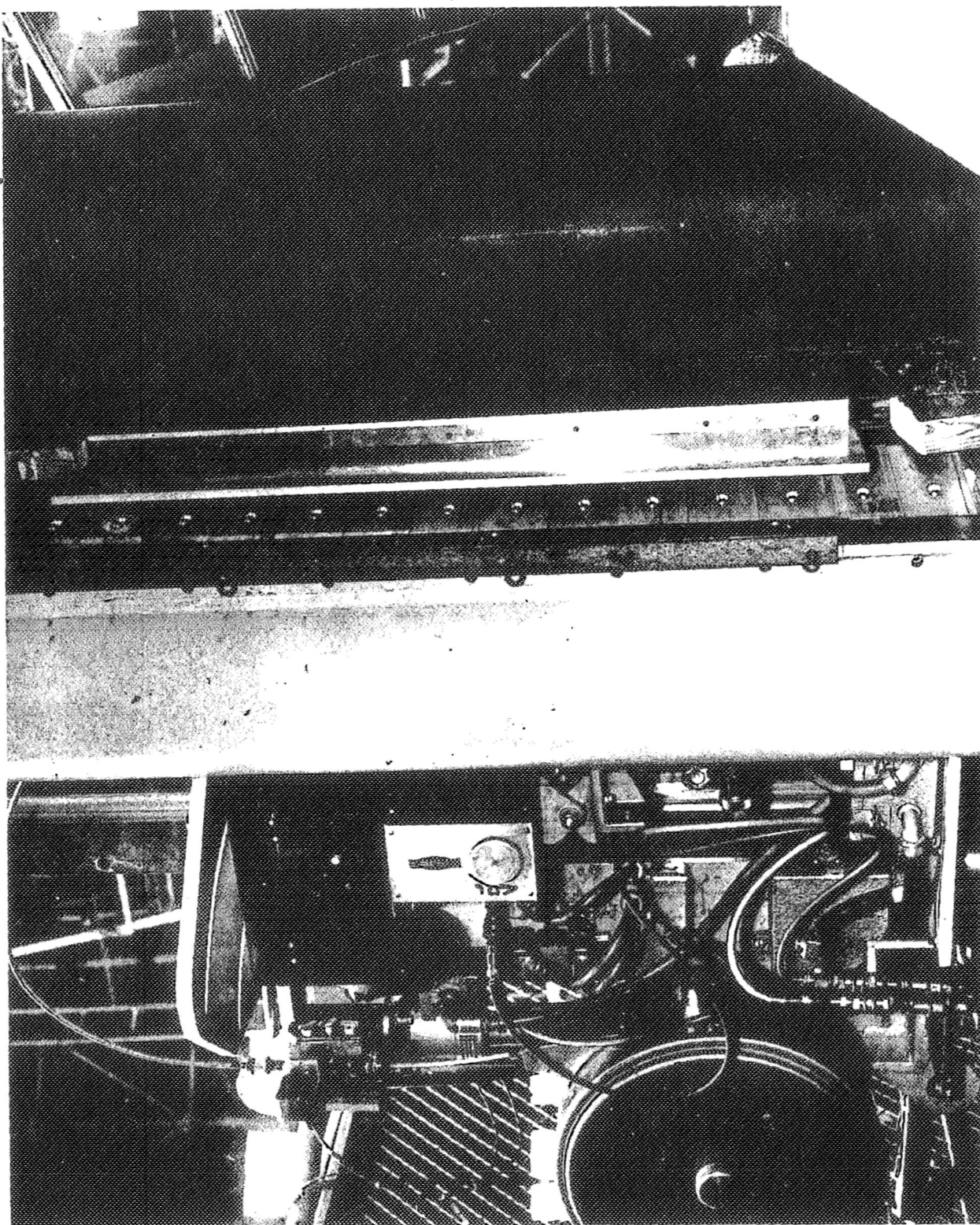


Figure 6. Test Setup for Phase II with Chill Tooling

## Phase II Results

### CRES Backing

To date, the results of Phase II reveal some interesting data regarding backing material and geometry. At a travel speed of 8 ipm with 3/8 inch wide CRES backing bars, increasing the bar spacing from 3/8 inch to 3/4 inch had no effect on the extent of the 300°F and 500°F temperatures. The required welding current was 10 percent less for the wider spacing. However, increasing the width of the CRES backing from 3/8 inch to 3/4 inch, with a constant 3/8 inch spacing, did effect the extent of the 500°F temperature rise at both welding speeds. This effect is shown in Figure 7. This change in backing geometry did not result in a change in the required welding current.

The backing geometry also was shown to exhibit a greater heat transfer influence at the lower welding speed. The results also indicate that increasing the hold down shoe pressure from 30 to 60 psig did not exert a discernible effect on the weld bead profile or heat transfer pattern with CRES backing.

### Copper Backing

The effect of copper backing gap and width on the heat transfer characteristics is shown graphically in Figure 8. As with CRES backing, the 3/4 inch spacing required approximately 10 percent less current than the 3/8 inch spacing. However, the heat transfer characteristics were significantly influenced by the backing groove width, although not as may have been anticipated. Increasing the backing groove width from 3/8 inch to 3/4 inch resulted in over a 10 percent reduction in the distance of the 300°F temperature from the weld centerline. More important, the distance the 500°F temperature extended into the base metal was reduced by approximately 25 percent. Duplicate tests are currently in work to verify these results.

Figure 8 also illustrates the influence of travel speed as the backing width is increased and the groove width is maintained constant. The data illustrates that the travel speed is less critical with copper backing. The effect of hold down shoe pressure was disclosed to exert a slight influence on heat transfer and, subsequently, the weld bead profile.

The influence of copper and CRES backing, 3/4 inch bars at 3/8 inch spacing, at two welding speeds is presented graphically on the left side of Figure 9. The data shows that both materials, at this backing geometry, resulted in uniform heat transfer at both travel speeds, with the copper restricting the heat flow through the base metal by approximately 15 percent.

The graph on the right side of Figure 9 shows the welding current as a function of travel speed and tooling (3/4 bars, 3/8 spacing). The present data indicates that the welding current is more sensitive to travel speed with CRES backing than with copper or no backing.

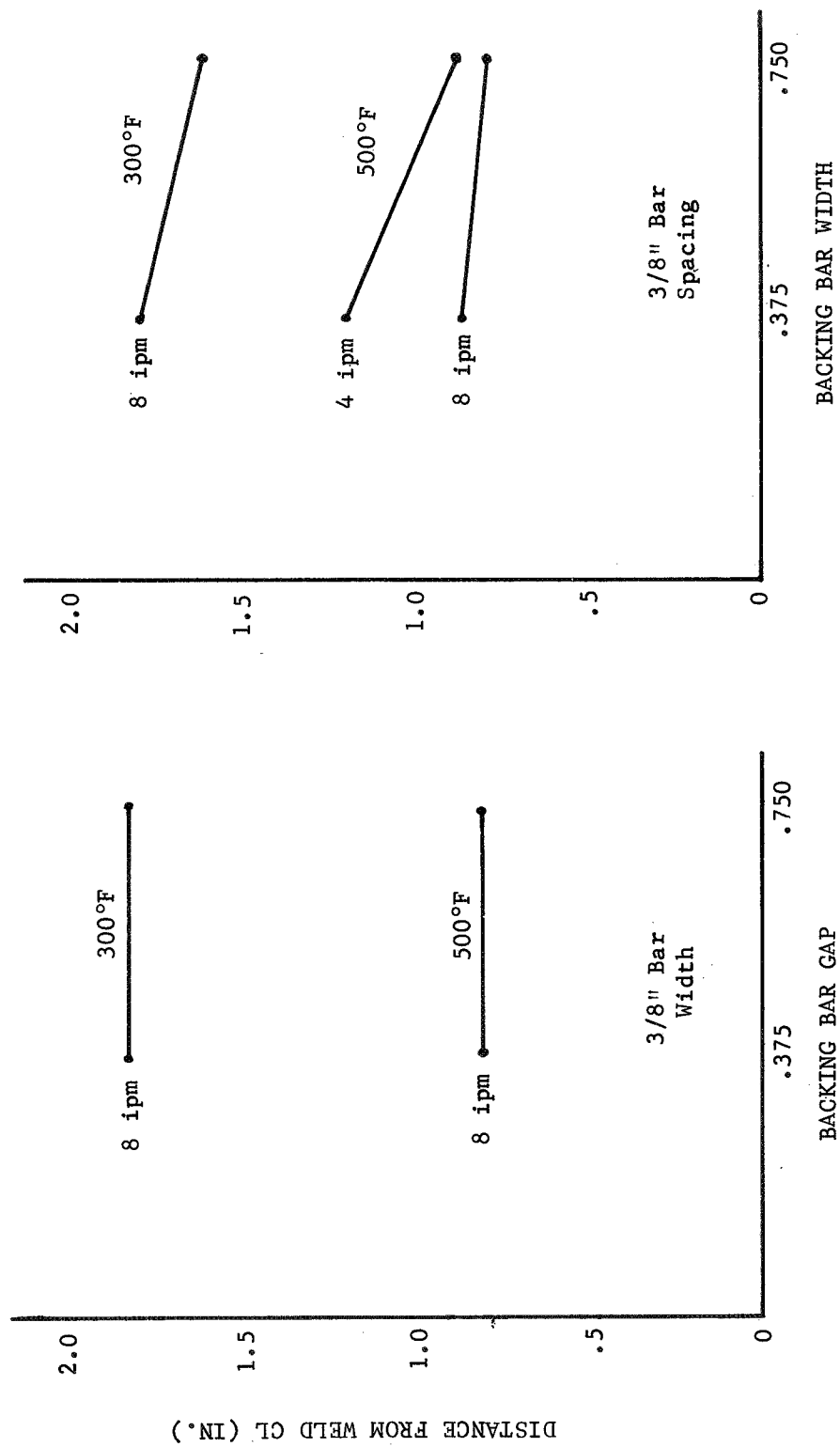


Figure 7. Effect of Cres Backing Geometry on Heat Transfer



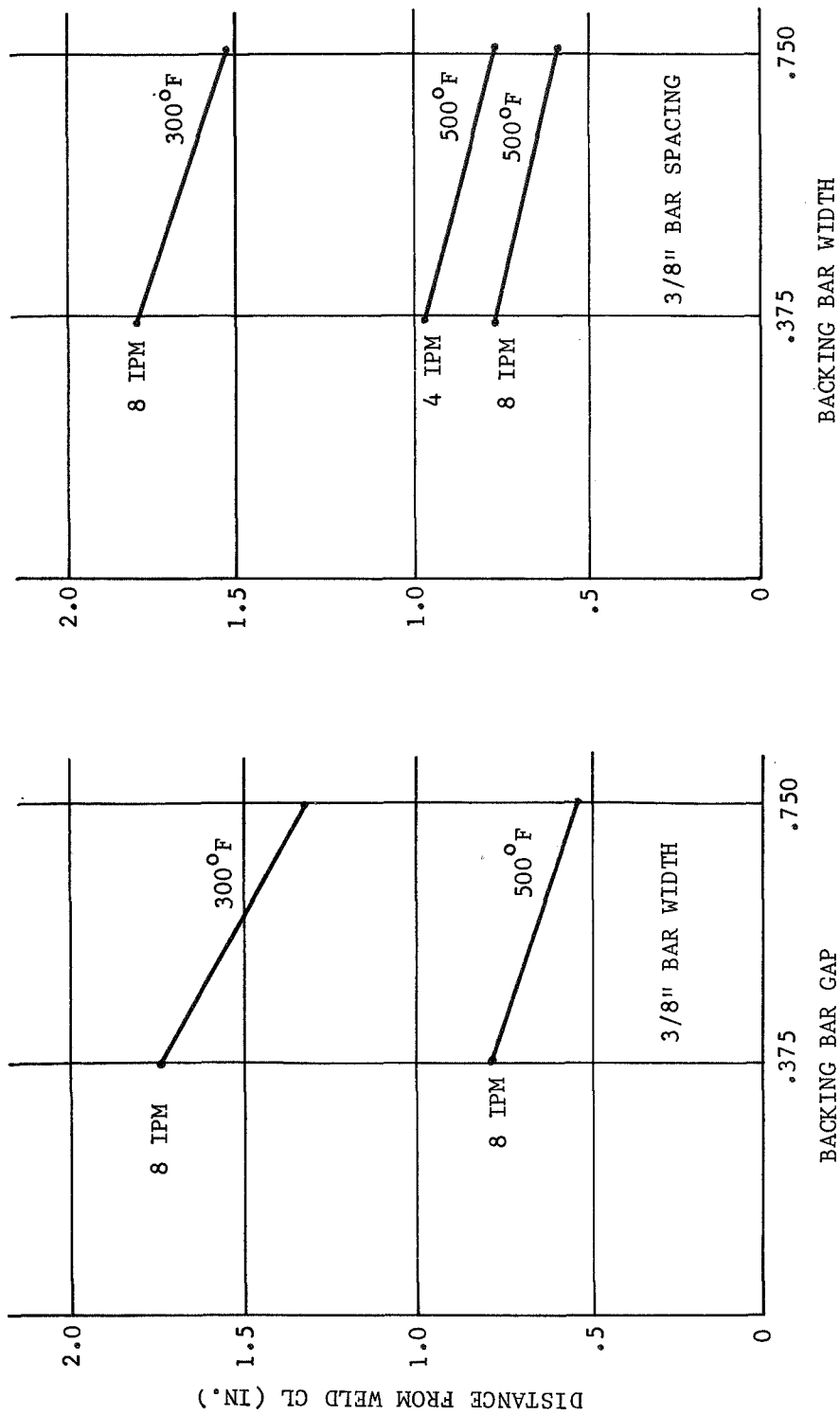


Figure 8. Effect of Cu Backing Geometry on Heat Transfer

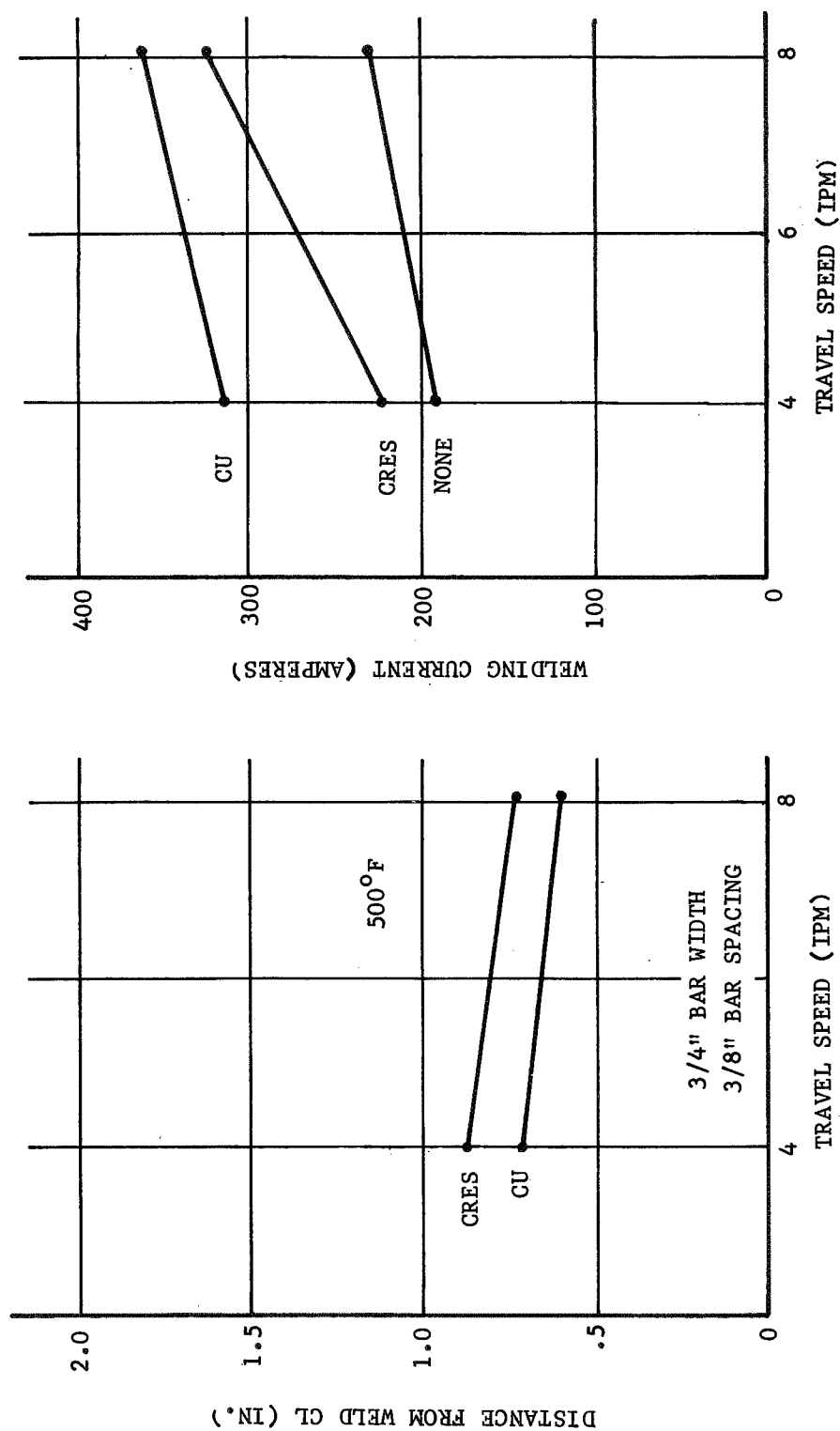


Figure 9. Effect of Backing Material on 500°F Temperature Rise of the Base Metal (left).  
The Graph on the right Relates Welding Current to Backing Material at Three Welding Speeds.

Figure 10 compares the effect of copper and CRES backing geometry on the 500°F temperature rise at two welding speeds. For comparative purposes, the graphs include the results of the same welding speeds without backing. The graphs illustrate that increasing the backing width, with a constant 3/8 inch spacing, significantly reduces the heat transfer to the base metal with both copper and CRES backing.

A comparison of the hardness values as influenced by the tooling material and travel speed is shown in Figure 11. This data indicates that the extent of property degradation of the base metal is not significantly affected by the backing material at the higher travel speed. The data also indicates that, as expected, the copper backing material is superior to CRES in reducing the heat affected zone at both travel speeds.

Figure 12 shows a comparison of the hardness values as influenced by weld backing at a welding speed of 4 ipm. The hardness outside of the weld fusion zone is significantly increased by the use of weld backing.

Figure 13 presents a hardness comparison at 8 ipm welding speed. Again, the hardness outside the fusion zone is significantly higher with weld backing.

From the preliminary data and results of this program to date, the following conclusions can be made:

1. Heat transfer into the base metal is significantly reduced by increasing the welding speed.
2. A total plate width of 20 times plate thickness is not sufficient for establishing relevant welding data, without tooling, to be applied to larger weldment widths.
3. Increasing the groove width of stainless steel backing does not appreciably affect the heat transfer profile. However, increasing the backing width does reduce the heat transfer characteristics.
4. The heat transfer profile is appreciably affected by varying the groove width and mass (width) of copper backing.
5. The welding amperage is considerably higher for copper backing, though not greatly affected by changes in travel speed. The amperage variation with respect to welding speed is more critical with stainless steel backing.
6. The heat transfer and weld bead profiles do not appear to be significantly affected by variation of clamping pressure with copper and stainless steel backing.

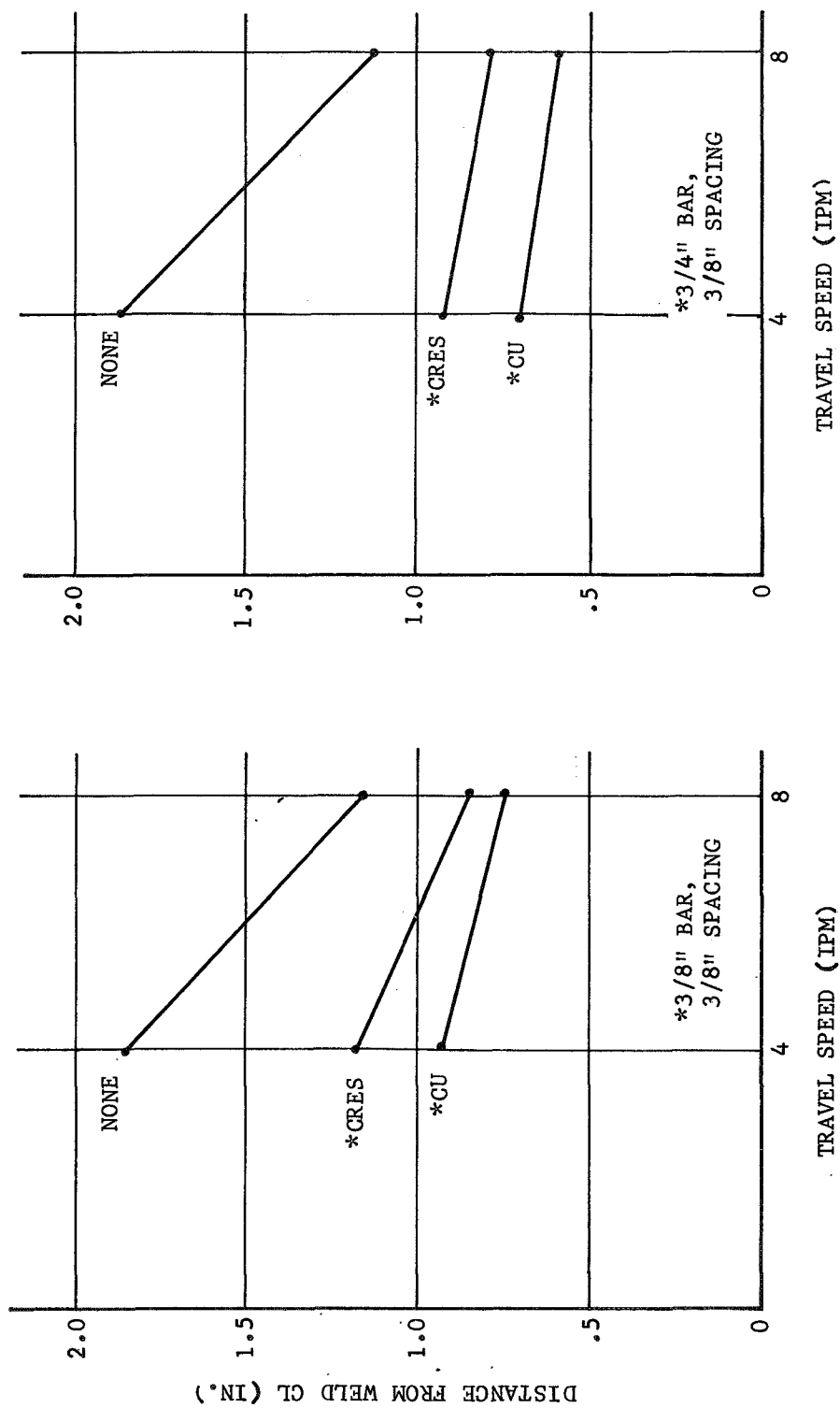


Figure 10. Effect of Backing Material and Geometry on the 500°F Temperature Rise of the Base Metal at Two Welding Speeds

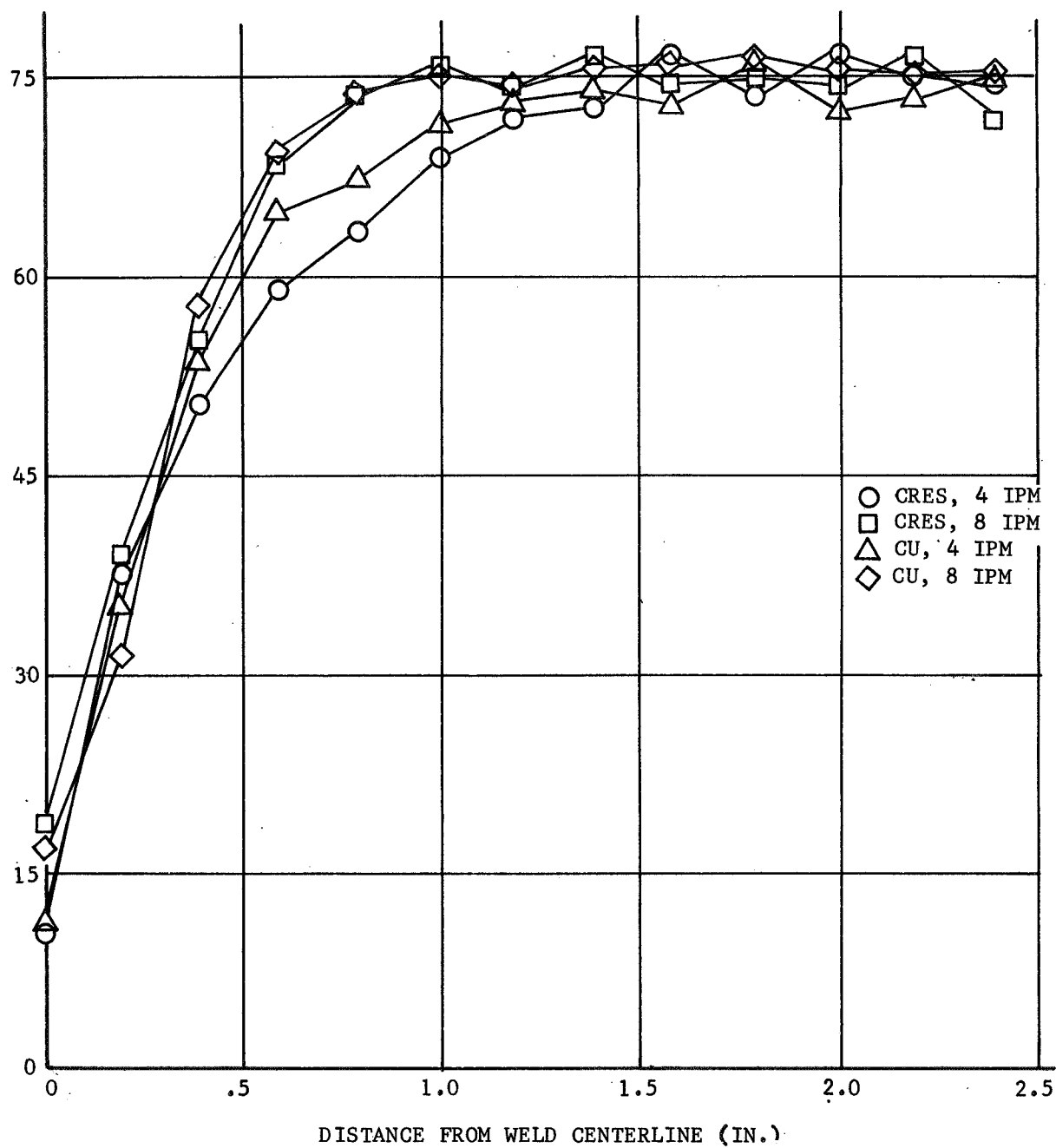


Figure 11. Influence of Backing Material and Travel Speed on Hardness

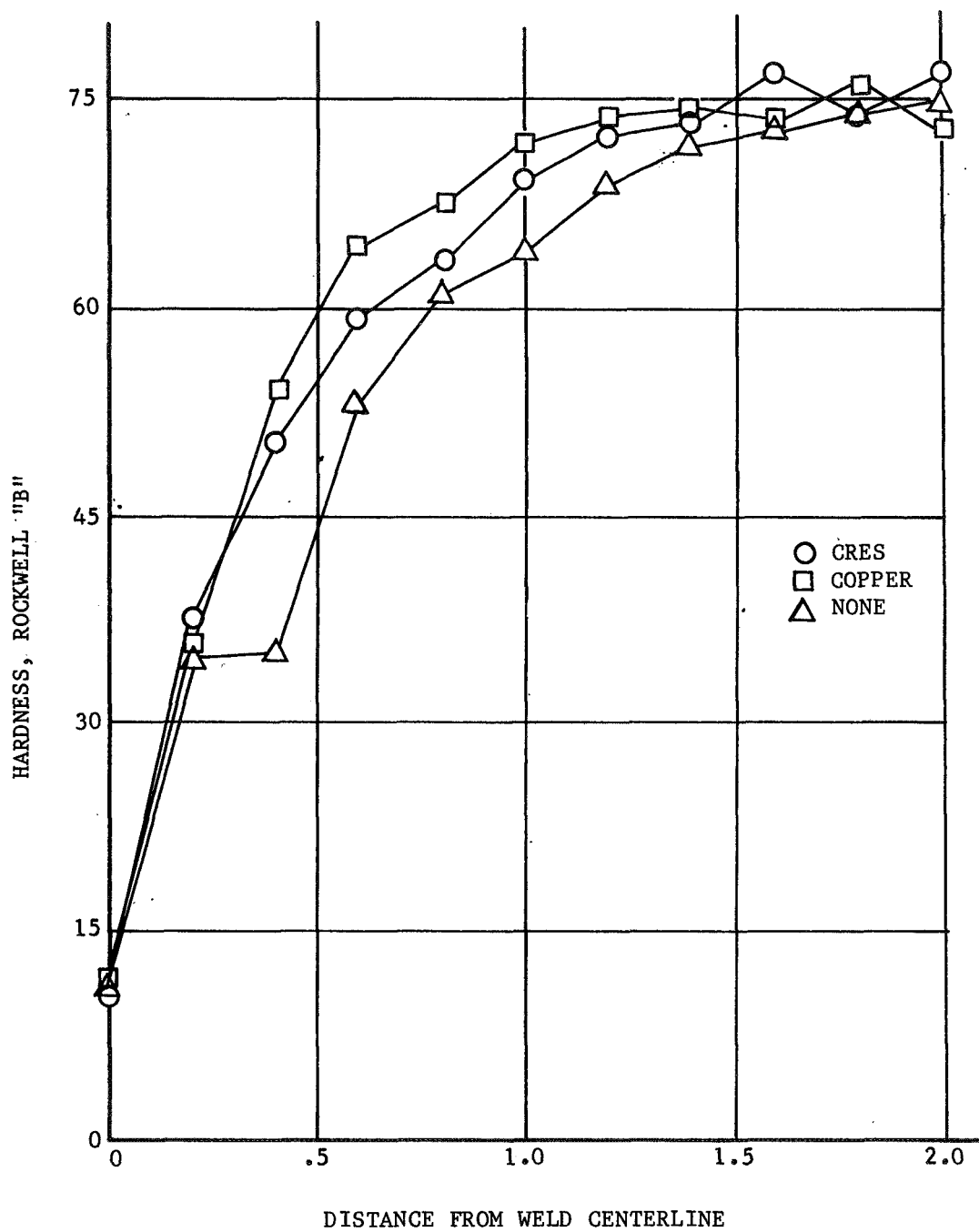


Figure 12. Hardness Values as a Function of Weld Backing at 4 ipm Welding Speed

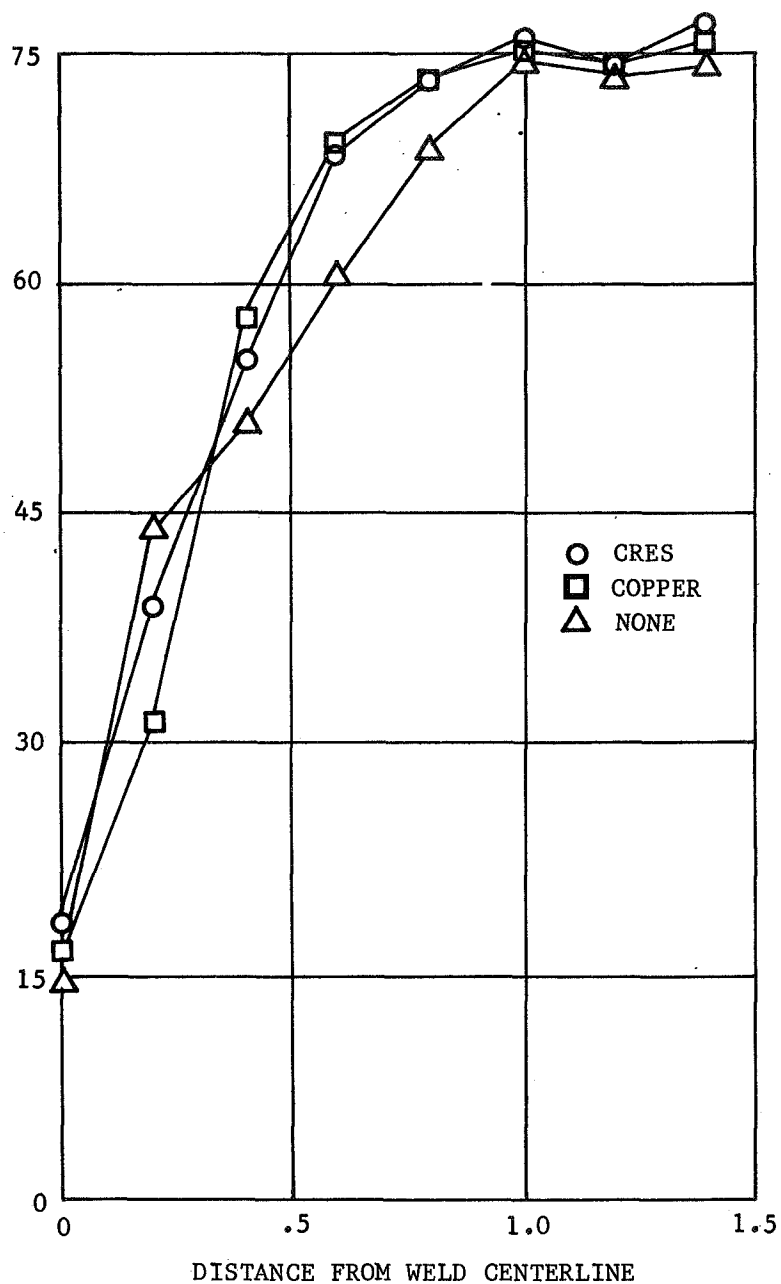


Figure 13. The Influence of Weld Backing on the Hardness Values at 8 ipm Welding Speed

## DISCUSSION

Mr. Chyle: Are there any questions? Yes, Mr. Saperstein?

Mr. Saperstein: In some work we found heat-affected zone failures, and this was certainly not too common, the failures occurred very close to the fusion line. It seemed, in many cases, at least to occur in this region partially because of resolution, in this case, of 2219. A similar reaction occurs in 2014, a resolution of the precipitated phase; hence, a very substantial softening in the region adjacent to the fusion line where the temperature exceeds 700°F, probably temperatures up above 850°F, very close to the melting point. I wondered if you looked at the time-temperature relationship above 700°?

Mr. Cline: We found that our original thermocouple instrumentation array was not close enough to the weld bead. So, some holes were drilled through our vacuum bars to get the thermocouples much closer to the weld center line, and in the final analysis, when this work is completed and transmitted to Marshall, the document will contain the heat transfer and the heat time-temperature relationships very close to the weld zone.

Mr. Wuenschel: Will you repeat once more which gage you used?

Mr. Cline: We welded .375 inch.

Mr. Chyle: I noted from one of your slides that as your speed increased, your amperage went up. Did this amperage go up without changing the parameters of the welding conditions?

Mr. Cline: We maintained arc voltage constant; we maintained wire feed rate constant, and everything was maintained constant within very close conditions during the entire welding program.

Mr. Chyle: And yet you had to increase current?

Mr. Cline: We had to increase current with a corresponding increase in travel speed or tooling change.

Mr. Chyle: Using a constant potential power source?

Mr. Cline: Using a direct current, straight polarity, constant current power source.

Miss Brennecke: In order to maintain the same area of melt when going faster, didn't you have to put in more heat?

Mr. Cline: On a plate width of 7½ inches, we had too much heat. Our weld-bead profile was not consistent with that which we desired.

Miss Brennecke: You were aiming for a constant profile?



Mr. Cline: It was constant as the plate width was increased to 15 and 22½ inches which is 4 OT and 6 OT. The conclusion is that with tooling, a plate thickness-to-width ratio of 2 OT is inadequate.

Miss Brennecke: There was a lag in reaction time, I would assume, with the lacquer, so that actually where the lacquer was melting had the material been at a higher temperature?

Mr. Cline: It might have been at a higher temperature, but our thermocouples are drilled and swaged right near the surface, also, in many cases, we were measuring surface temperature.

Miss Brennecke: I am wondering how much correlation there was between the thermocouple measurements and the reaction from the lacquer. In other words, how many tests would you be willing to run now with lacquer and without thermocouples?

Mr. Cline: I would be willing to run a great number because I've found that the specifications of the lacquer manufacturers of  $\pm 1$  percent are quite accurate.

Mr. Chyle: Are there any other questions? Yes?

Question: Just one additional question. I wonder if you measured the difference in temperature between the top and bottom surfaces?

Mr. Cline: No, we did not. With the tooling, it was difficult because we had the clamping shoes on one side and the backing material on the other side. We have not attempted to measure the temperature difference between the face side of the plate and the root side of the plate. However, we know there must be some temperature difference.

Mr. Chyle: Mr. Cline, we will have to close this discussion, and we want to thank you for a very fine paper.

STRAIN DISTRIBUTION AND FAILURE MECHANISMS  
IN 2219-T87 ALUMINUM WELDMENTS

By

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## INTRODUCTION

The strength-to-weight ratios of high strength aluminum alloys make them attractive for structural applications in space vehicles. Weldability problems inherent in a number of these alloys limit their use. Research programs have indicated that 2219-T87 has excellent weldability. This alloy is being used in several space programs.

The reduction of the load carrying capacity of 2219-T87 upon welding results from the lower strength of the weld deposit and the heat affected base metal. The mechanical properties of 3/4 inch thick 2219-T87 weldments have been evaluated at Southwest Research Institute. In particular, the strain distribution which occurs within the 2 inch gauge length frequently used for elongation measurements has been studied. The strain distributions at the yield strength (0.2 percent offset) and ultimate tensile strength stress levels have been determined.

Fracture surfaces of these weldments were examined metallurgically and by the electron fractographic technique to study failure mechanisms. Both uniaxial tensile test specimens and biaxially loaded 3/4 inch thick welded panels displayed similar failure mechanisms.

## Strain Distribution In 2219-T87 Aluminum Weldments

### Specimen Preparation

All specimens used in the study were from 3/4 inch thick 2219-T87 aluminum welded panels. These panels were fabricated by butt-welding two 8 x 24 inch plates in the horizontal position. Welding was carried out automatically by the Tungsten Inert Gas Process using a Linde HWM-2 mechanized contour welder. A square-butt weld preparation was used with a single pass deposited from each side. The welding operation is shown schematically in Figure 1. Welding parameters were as follows:

Amps	380
Volts	11.5
Carriage Travel Speed	7 ipm
Cold Wire Feed	9 ipm
Gas Flow (Helium)	60 cfh
Filler Metal	3/64 inch diameter 2319
Electrode	Tungsten (thoriated) 5/32 inch diameter

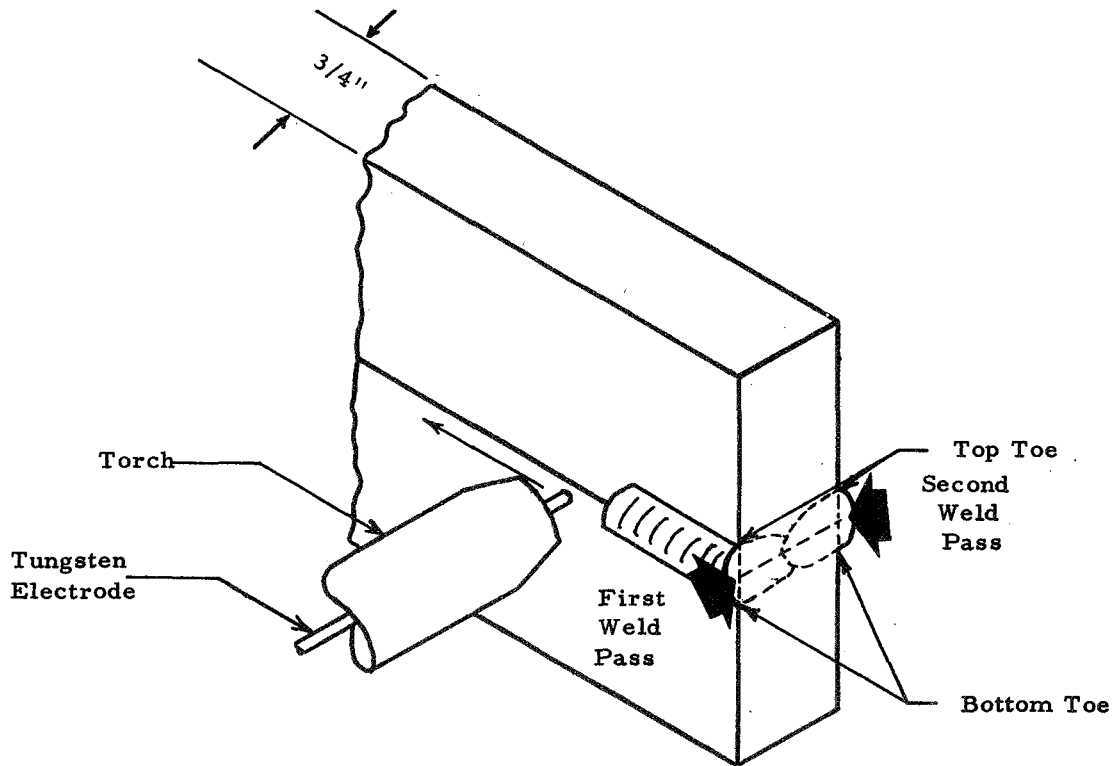


Figure 1. Schematic of Tungsten Inert Gas, Horizontal Welding of 3/4 Inch, 2219-T87 Aluminum Panels

A typical weld cross section is shown in Figure 2. The second pass deposited is seen to overlap part of the first pass. Toes of the first and second weld passes are also indicated in Figure 2.

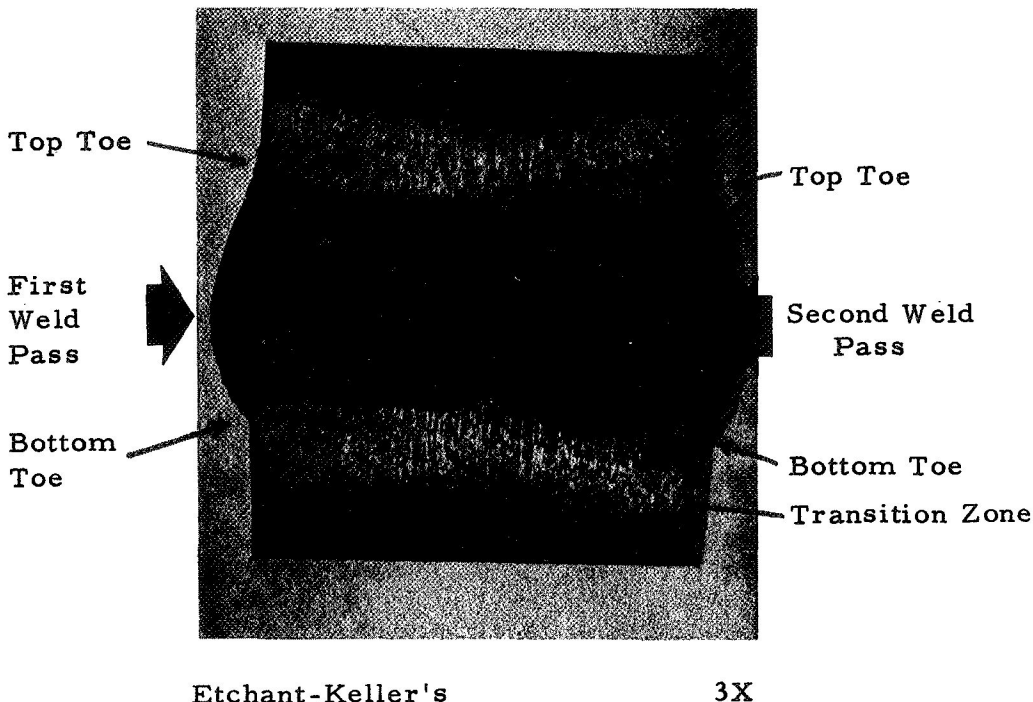


Figure 2. Typical Cross Section of a Two Weld Pass Square Butt 2219-T87,  
3/4 Inch Thick Weldment

#### Specimen Design

The uniaxial tensile specimen shown in Figure 3 was used to determine the mechanical properties and to evaluate the strain distribution of the weldments. This specimen was designed to test the transverse properties of the weld with the weld crowns intact. The joint efficiency for these weldments as determined using this specimen design was approximately 62 percent.

#### Stress-Strain Distribution At Yield Strength

Miniature strain gages were mounted in the weld metal and in two locations of the heat affected base metal of uniaxial tensile specimens. One gage was mounted 1/32 inch from the weld fusion line. This was in one of two areas approximately 1/16 inch wide, immediately adjacent to the weld fusion lines. These regions are hereafter referred to as the transition zones. The extent of a transition zone is shown in Figure 2. The other strain gage in the heat affected base metal was mounted 1/2 inch from the weld fusion line. Locations of the three strain gages are shown in Figure 3.

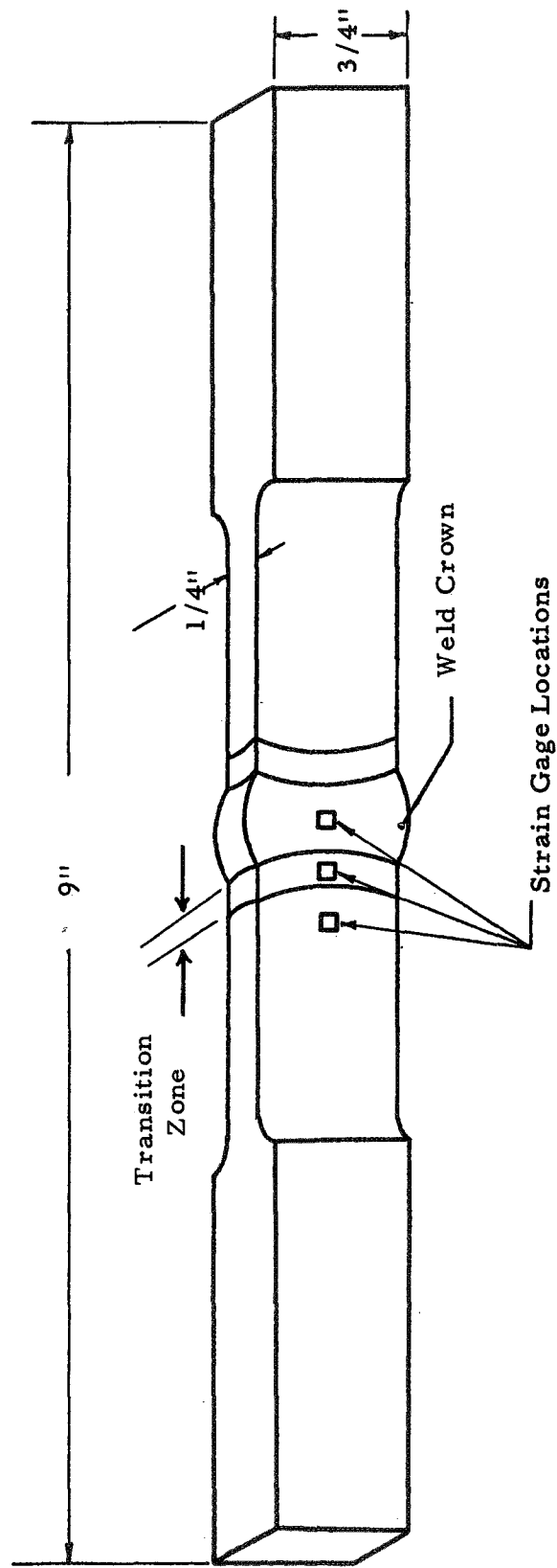


Figure 3. Uniaxial Tensile Specimen Configuration

Stress-strain curves for each of these discrete locations were plotted from miniature strain gage data. These curves and the 2 inch gage length extensometer stress-strain curve are compared in Figure 4. The large variation in the load carrying capacity of the different regions of the weld zone is indicated by the shape of the curves.

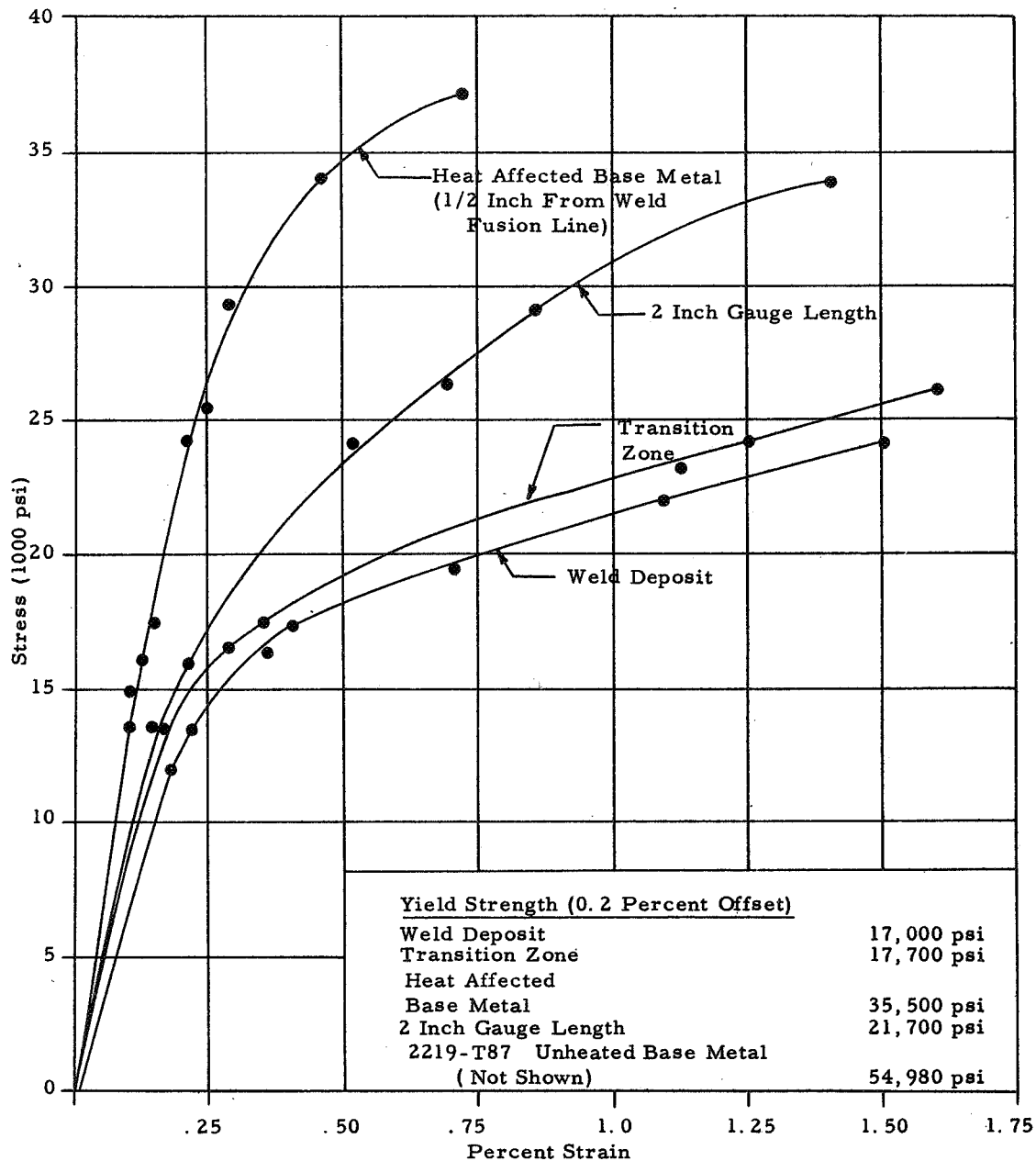


Figure 4. Typical Stress-Strain Curves of Weld Deposit, Transition Zone and Heat Affected Base Metal (1/2 Inch Form Weld Fusion Line) of a 2219-T87 Welded Joint. Derived from Miniature Strain Gage Data

Using these curves, the 0.2 percent offset yield strength was determined for the strain gage locations and the overall 2 inch gage length. Sets of 0.2 percent yield strength values from three tensile specimens were averaged and compared with the 0.2 percent yield strength of 3/4 inch thick 2219 plate in the T87 condition (54,980 psi, average of six specimens). The results were as follows:

2219-T87 Plate	100 Percent
Heat Affected Base Metal	
(1/2 Inch From Fusion Line)	66 Percent
Transition Zone	32 Percent
Weld Metal	29 Percent
Overall 2 Inch Gage Length	42 Percent

These comparative values indicate the extent to which the lower strength of the weld metal and the transition zone contribute to the reduced yield strength of 2219-T87 weldments.

#### Weld Zone Strain Distribution From Simultaneous Stress-Strain Curves

The simultaneous stress-strain curves shown in Figure 4 illustrate the reaction to tensile loading of the individual components (weld metal, transition zone and heat affected base metal) which comprise the 2 inch gauge length. Table I tabulates the strain values for these components at four stress levels ranging from 15,000 to 24,000 psi (0.2 percent yield strength from 2 inch extensometer was 21,700 psi). The percentage contribution of each component to the overall increase in length which was measured by the extensometer at each stress level is also given in Table I. The stress-strain curves shown in Figure 4 illustrate the successive plastic yielding which occurs initially in the weld metal, then in the transition zone and finally in the heat affected base metal as the applied stress exceeds their respective yield strengths. Table I shows that the contribution of the weld metal and the transition zone to the overall increase in length of the 2 inch gauge section doubled as the applied stress increased from 15,000 to 24,000 psi.

#### Weld Zone Plastic Strain Distribution At Ultimate Tensile Stress

The strain distribution across the weld zone determined from simultaneous stress-strain curves represents the combined elastic and plastic strains which result from a given stress. As the magnitude of the applied stress approaches the ultimate tensile strength of the weldment, the resulting strains become predominantly plastic in the weld metal and in the transition zone. However, the plastic component of the total strain of the heat affected base metal at the ultimate stress level is a function of the extent of aging effects which have occurred during welding. The plastic strain component can be expected to be large immediately adjacent to the transition zone and decrease rapidly to a lower magnitude at the outer limit of the 2 inch gauge section. Failure will occur when the applied stress level reaches the ultimate strength of the weldment. After failure, the elastic component of the total strain will no longer exist. On the other hand, the plastic components of the total strain which existed in each zone immediately prior to failure produced permanent changes in



Table I. Strain Distribution in a 2219-T87 Weldment at Stress Levels Close to Yield Strength<sup>1</sup> as Determined by Miniature Strain Gages

STRESS PSI	STRAIN DISTRIBUTION (PERCENT STRAIN)				PERCENTAGE OF TOTAL EXTENSION ACROSS WELDED JOINT (2 INCH GAUGE LENGTH) CONTRIBUTED BY EACH ZONE <sup>2</sup>			
	WELD METAL	TRANSITION ZONE	HEAT AFFECTED BASE METAL	2 INCH GAUGE LENGTH	WELD METAL	TRANSITION ZONE	HEAT AFFECTED BASE METAL <sup>3</sup>	2 INCH GAUGE LENGTH
15,000	.28	.22	.11	.18	29.0	6.0	65.0	100.0
17,500	.40	.35	.14	.25	30.0	7.0	63.0	100.0
21,700	1.03	.80	.18	.40	48.0	10.0	42.0	100.0
YIELD STRESS								
24,000	1.50	1.21	.21	.53	54.0	12.0	34.0	100.0

1 Yield Strength (0.2 percent offset) for 2 inch gauge length from extensometer.

2 Percentage of Total Extension =  $\frac{\text{Percent Strain} \times \text{Width}}{100}$  For A Zone  
 Weld Metal = .375 Inches Wide  
 Transition Zone = 2 x .050 Inches Wide

3 Percentage of total extension across welded joint (2 inch gauge length) contributed by the heat affected base metal = 100 percent minus the sum of the percent contributions of the weld metal and the transition zone.

the dimensions of these zones. Thus the plastic strain distribution which existed in the weldment at the ultimate stress level can be determined by measuring the width of each zone before and after testing.

Prior to testing, the tensile specimens were etched to identify the weld metal and transition zone. Knoop hardness indentations were placed at the boundaries of the various zones. A travelling microscope was used to measure the width of each zone before and after testing. Figure 5 is a schematic representation of the zones within the 2 inch gauge length. The three surveys made were through the first weld pass, the weld intersection and the second weld pass. Since failure always occurred in the weld metal, the final width of the weld zone was the sum of the distance from both weld fusion lines to their respective fracture edges.

The values obtained using this procedure are listed in Table II. The average strain values shown for the three zones are the plastic strains which existed in the weldment when the applied stress reached the ultimate strength. These values emphasize the extent to which plastic strain is concentrated in the weld metal and in the transition zone of 2219-T87 weldments. On the basis of five specimens surveyed, the average strain values determined for the weld metal, transition zone and heat affected base metal were 19.6, 8.7 and 0.97 percent respectively. The gross plastic deformation which the weld metal and the transition zone underwent prior to failure are not reflected by the percent elongation value (5.9 percent) calculated in the 2 inch gauge length.

This is accounted for by two factors. The first factor is the low plastic strain value exhibited by the heat affected base metal. The second factor is the low width of the weld metal and transition zone as compared to the heat affected base metal within the 2 inch gauge length. A more meaningful percent elongation value for 2219-T87 weldments would result if the overall width of the gauge section was limited to include only the weld metal and the transition zone.

Table II also lists values for the percentage of the total extension across the 2 inch gauge length contributed by each zone. The plastic deformation which occurred in the weld metal makes up 57.1 percent of the total increase in length. This compares favorably with the corresponding value determined from the simultaneous stress-strain curves. The values determined for the transition zone contributions by the two methods are also in close agreement. The contribution of the heat affected base metal to the overall change in length of the 2 inch gauge section determined after failure is considerably less than the value obtained at the 0.2 percent yield stress level. The smaller value represents plastic strain only while the larger value at yield stresses represents both plastic & elastic strains.

The low average strain of the heat affected base metal in Table II is not an indication of low ductility. It is an indication that this region has higher strength than the weld metal and transition zone and was not highly stressed above its yield point.

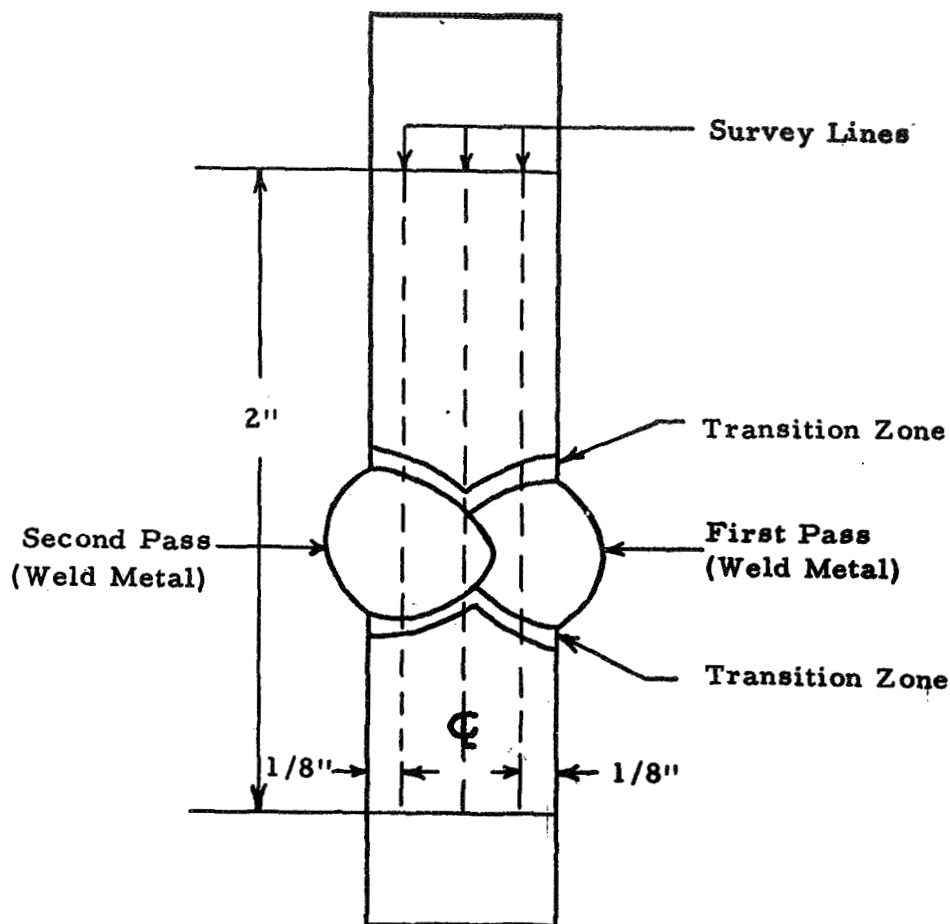


Figure 5. Schematic of Surveys on the Reduced Section of a Tensile Sample to Measure Strain in Various Zones

#### Failure Mechanism In 2219-T87 Aluminum Weldments

Fracture initiation for a series of 40 tensile specimens always occurred in the first weld pass. Evidence of this was provided by butting the failed tensile specimens together. In all cases a gap was noted in the first weld pass. A typical gap is shown in Figure 6. This gap was always in the bottom toe and fracture was always diagonally through the weld in these tensile specimens.

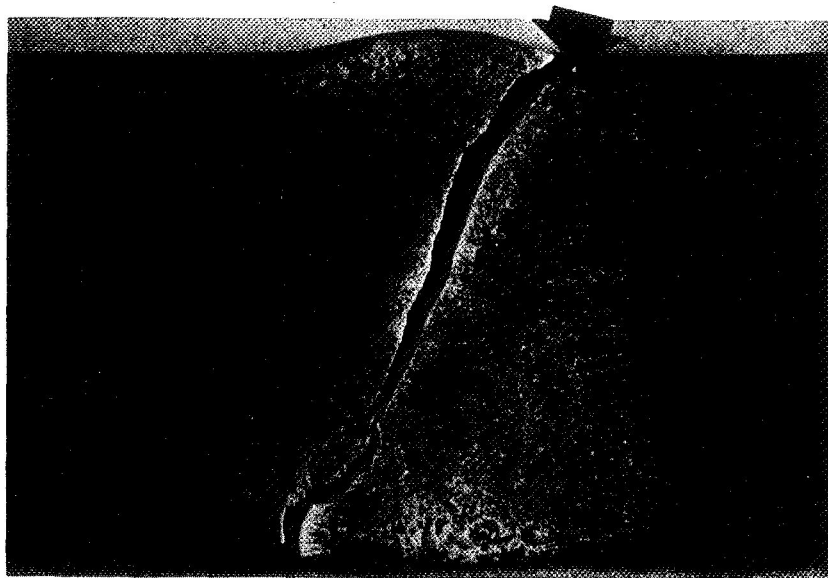
Table II. Summary of Average Strain in Weld Metal, Transition Zone and Heat Affected Base Metal of Welded 3/4 Inch Thick 2219-T87 Aluminum Tensile Specimens Determined After Failure.

SPECIMEN	AVERAGE PERCENT STRAIN IN WELD ZONES <sup>1</sup>				PERCENT ELONGATION OVER 2 INCH GAUGE LENGTH
	WELD METAL AVERAGE STRAIN (PERCENT)	TRANSITION ZONE AVERAGE STRAIN (PERCENT)	HEAT AFFECTED BASE METAL AVERAGE STRAIN (PERCENT)		
27-2	21.2	6.8	1.09		5.25
27-3	19.9	9.6	0.95		6.15
33-4	18.9	10.1	0.38		6.20
33-5	20.5	8.7	1.09		6.20
33-6	17.3	8.7	1.33		5.60
AVERAGE	19.6	8.7	0.97		5.9
PERCENTAGE OF TOTAL EXTENSION ACROSS WELDED JOINT (2 INCH GAUGE LENGTH) CONTRIBUTED BY EACH ZONE	57.1*	2.(4.2*)= 8.4	12.9*		100.0

\* THE SUMMATION OF THESE VALUES IS NOT 100 PERCENT. THIS IS THE RESULT OF THE GAP OCCURRING ACROSS THE FRACTURE.

$$1 \text{ PERCENT STRAIN} = \frac{\Delta l}{\text{INITIAL LENGTH}} \times 100$$

Gap At  
First Pass  
Bottom Toe



Etchant - Keller's

3-1/2X

Figure 6. Appearance of a Typical Gap in the Fracture Path of a Broken Tensile Specimen After Butting the Failed Pieces Together

The fracture mechanism associated with this gap caused an apparent reduction in the ductility and hence in the plastic strain measurements of the first pass weld metal.

In Table II for the weld metal percent contribution to the elongation over 2 inches (57.1 percent) was the average for the first weld pass, second weld pass and intersection region of five specimens. The average corresponding values based on the individual surveys were as follows:

52.7 percent of the elongation for the 2 inch gage length occurred in the first weld pass.

59.2 percent in the weld intersection.

68.3 percent of the overall value was contributed by the second weld pass.

The lower strain values and the gap in the first weld pass were attributed to the initiation and growth of a crack preceding the final tensile failure.

The cause for initiation at the bottom toe of the first weld pass was found to be dependent on the geometrical notch afforded by the weld crown and also to the presence of a metallurgical notch. Both of these factors were studied.

To evaluate the geometrical notch effect, specimens were tested with the weld crown machined flush with the weld plate. The failed tensile specimens no longer exhibited a gap in the first weld pass. Surveys across the weld zone indicated that the strain in the first weld pass had increased considerably. Table III compares the weld metal contribution towards the 2 inch elongation value in tensile specimens tested with and without weld crowns. With the weld crown removed, the first pass weld deposit now accounted for 75.8 percent of the elongation measurement. Further evidence of crack initiation as a result of the notch in the toe of the weld crown was provided by depositing fusion passes in the bottom toes and in all four toes. Figure 7 schematically shows the location of these fusion passes and lists the welding parameters. The fracture path through the weld varied in these tensile specimens. Furthermore, the elongation in the 2 inch gauge length increased when the fusion passes were placed in the bottom toes. Table IV contains a summary of the mechanical properties of specimens tested with and without these fusion passes.

Table III. Comparison of the Percentage of the 2 Inch Elongation Contributed by Weld Metal in Tensile Specimens With and Without Weld Crowns

SURVEY	PERCENTAGE OF 2 INCH ELONGATION (2 INCH GAUGE LENGTH) CONTRIBUTED BY THE WELD METAL	
	WELD CROWN ON <sup>1</sup>	WELD CROWN OFF <sup>2</sup>
FIRST WELD PASS	52.7	75.8
WELD INTERSECTION	59.3	57.9
SECOND WELD PASS	68.3	70.8

<sup>1</sup> AVERAGE OF 5 SPECIMENS

<sup>2</sup> AVERAGE OF 3 SPECIMENS

Table IV. Summary Of Average Mechanical Properties Of 3/4 Inch Thick 2219-T87 Aluminum Weldments With And Without Fusion Passes In The Toes Of Welds.

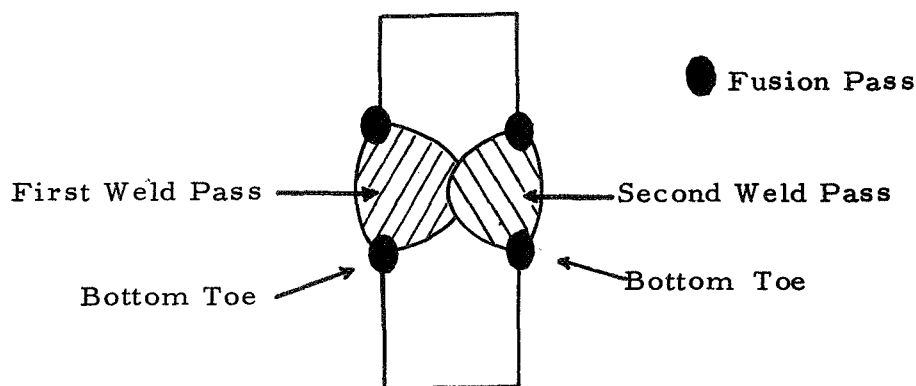
<u>Specimen</u>	<u>Yield Strength (0.2 Percent Offset) psi</u>	<u>Tensile Strength psi</u>	<u>Percent Elongation (in 2 inches)</u>
Fusion passes in top toes of weldment <sup>1</sup>	23,080	41,250	5.3
Fusion passes in bottom toes of weldment <sup>1</sup>	22,180	43,100	6.7
Fusion passes in top and bottom toes of weldment	23,860	44,170	5.9
Weld crown on no fusion passes used <sup>2</sup>	23,080	43,460	5.88
Weld crown off no fusion <sup>3</sup> passes used	23,070	41,070	6.00

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<sup>1</sup> Average of 6 specimens

<sup>2</sup> Average of 5 specimens

<sup>3</sup> Average of 3 specimens



#### WELDING PARAMETERS FOR ALL FUSION PASSES

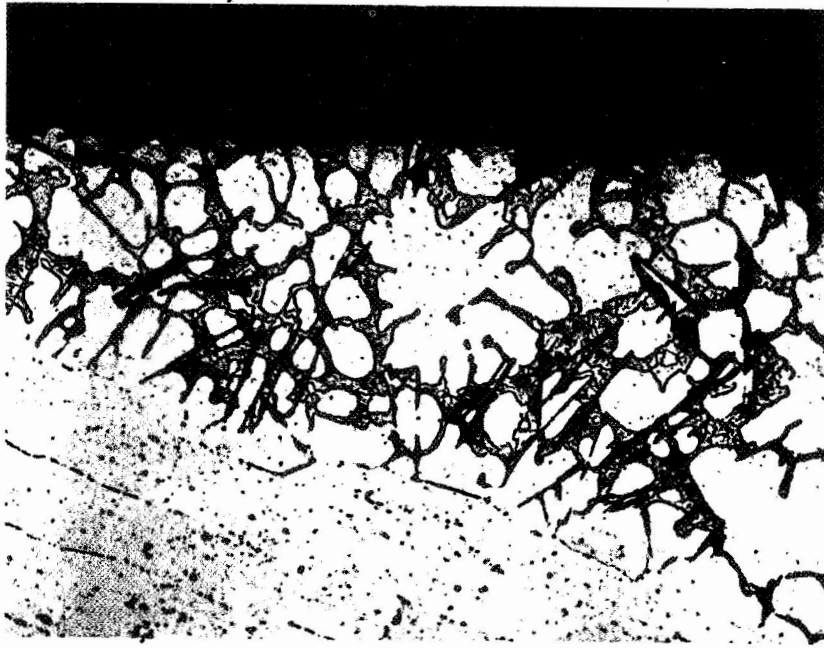
Amps	160
Volts	11.5
Carriage Travel Speed	7 ipm
Cold Wire Feed	9 ipm
Gas Flow (Helium)	60 cfh
Filler Metal	3/64 inch diameter 2319
Electrode	3/32 inch thoriated tungsten

Figure 7. Location of Fusion Passes in the Toes of the Weld and Their Welding Parameters

The nature of the metallurgical notch was also investigated. It was found that the welding thermal cycle could produce a high concentration of intermetallic constituents in the area of the weld toe. This is illustrated in Figure 8.  $\text{CuAl}_2$  has a Chinese script appearance and the needle-like phase is  $\beta$  (Al-Cu-Fe). The brittle nature of these constituents leads to premature cracking of the weld toe regions. Figure 9 is a photomicrograph illustrating this condition. The formation of these cracks was found to occur between 92 and 97 percent of the ultimate tensile strength (based on 3 tests). The final fracture initiates from one of these cracks.

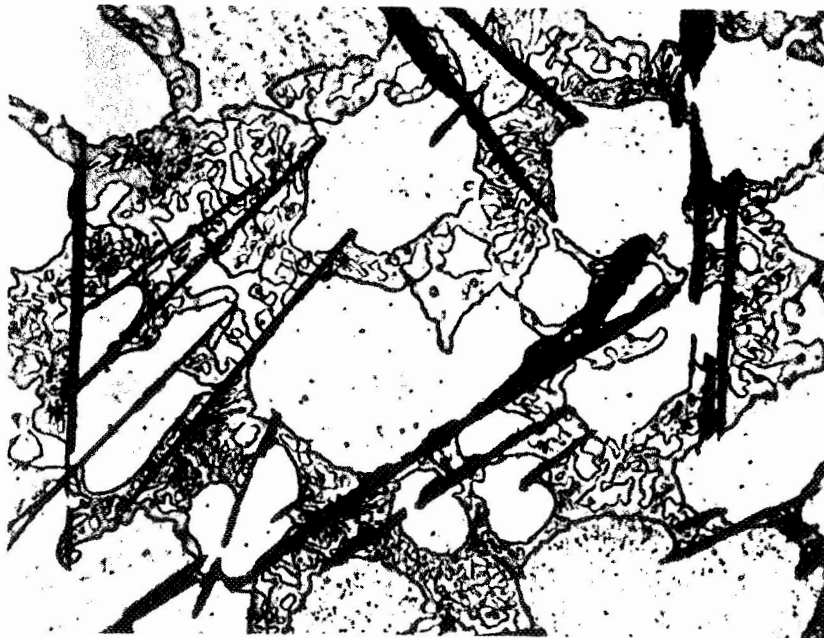
The fracture path was found to follow the intermetallic constituents. Evidence of this was found by sectioning failed tensile specimens. One of the areas where the crack propagates through the weld metal is shown in Figure 10. The failure path is intergranular and through the intermetallic constituents.





Etchant - Keller's

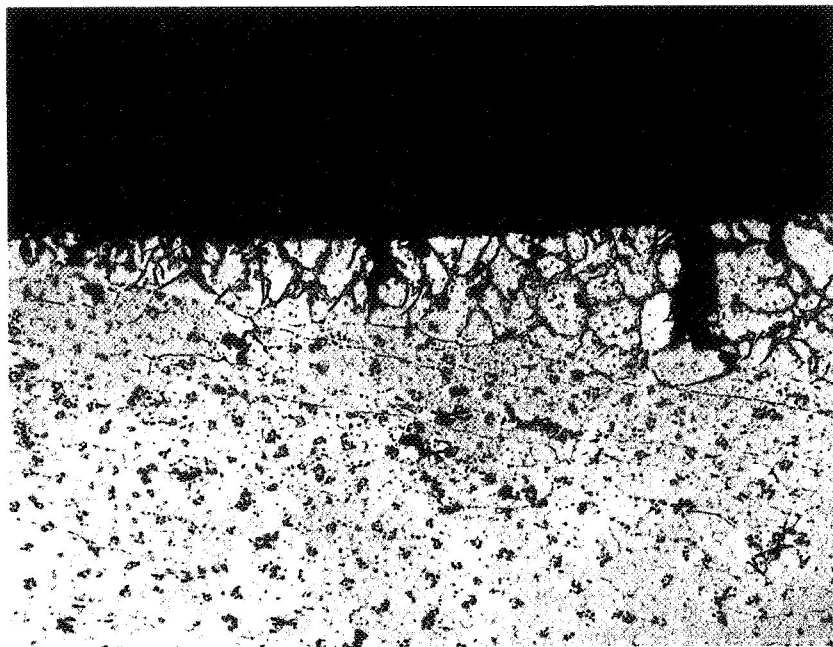
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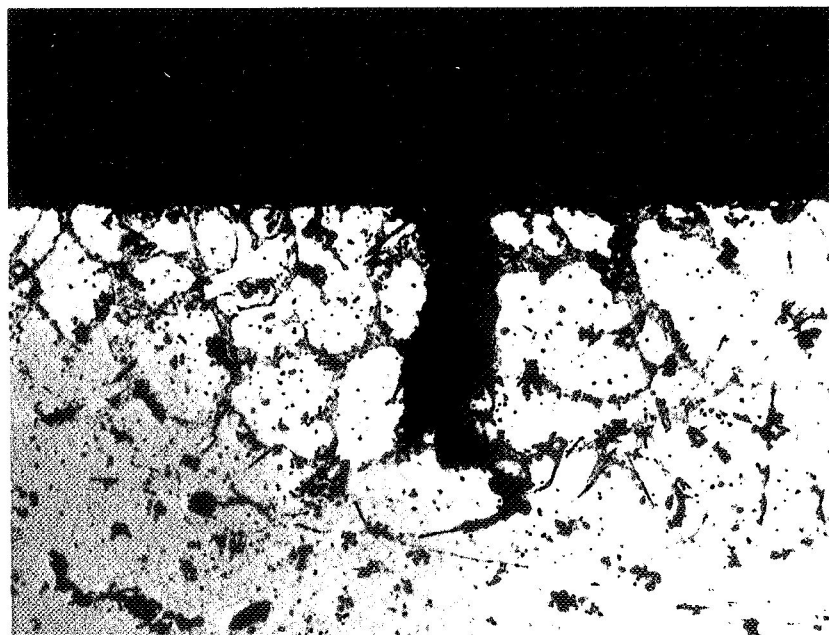
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Figure 8. Concentration of Intermetallic Constituents in The Bottom Toe of a Weld.



Etchant - Keller's

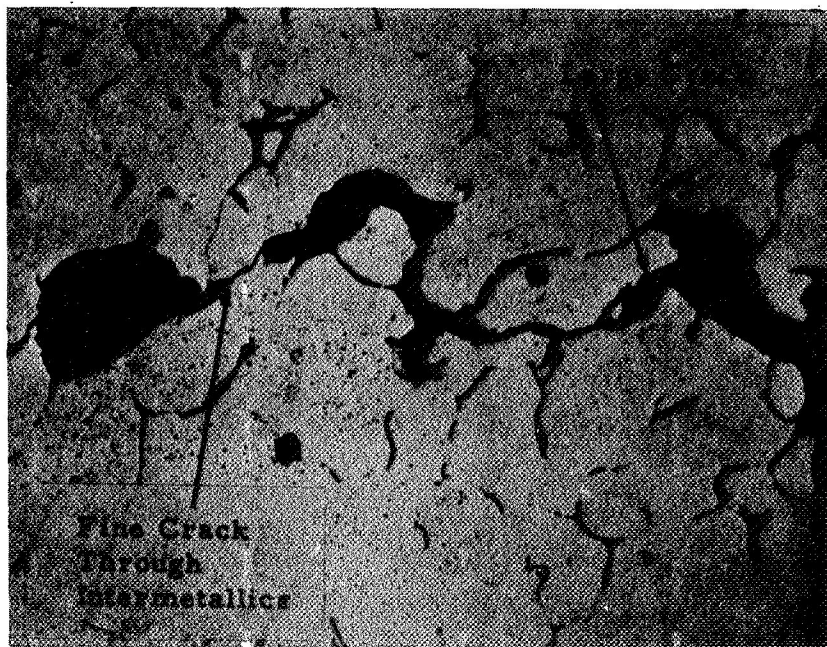
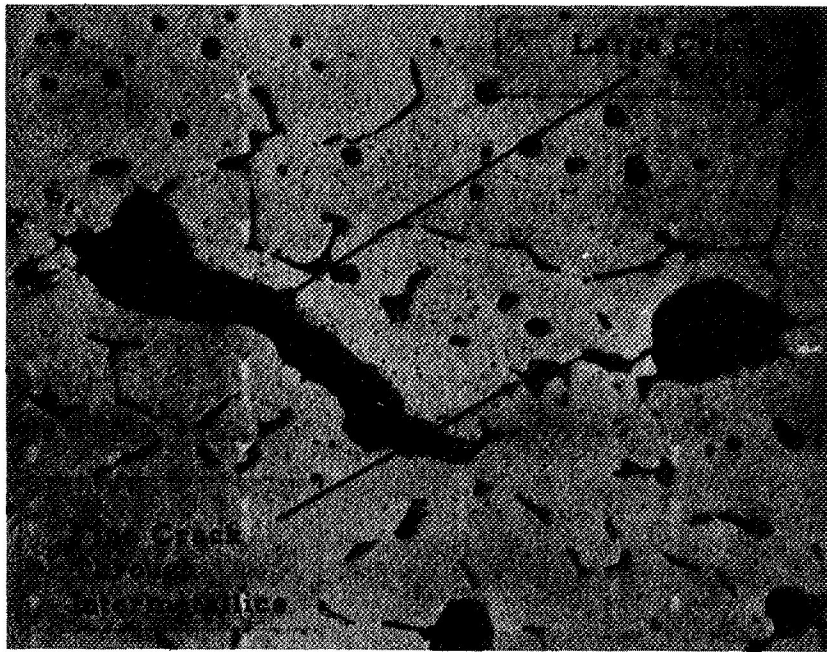
250X



Etchant - Keller's

500X

Figure 9. Formation of Cracks in The Intermetallic Constituents in The Bottom Toe of a Weld After Stressing



Etchant - Keller's

1000X

Figure 10, Cracks in Weld Deposit of Uniaxial Tensile Specimen After Failure. Note That The Cracks Follow The Path of Intermetallic Constituents

Fracture mechanisms in biaxial test specimens were found to be similar to those observed in uniaxial specimens. The biaxial specimens consisted of 3/4 inch thick welded panels (32 x 32 inches) tested in the hydraulic bulge fixture shown in Figure 11. This fixture consists of a top and bottom die between which the test panel is clamped. Hydraulic pressure is introduced between the test panel and the bottom die forcing the panel to bulge upward into the circular opening in the top die. The fracture in the toe of the weld of a 3/4 inch thick biaxial test panel is shown in Figure 12.

Electron fractography was also employed to study failure mechanisms. One indication from this technique was that ductile failure occurred in the weld metal. These ductile regions, however, were well removed from the toes. This is illustrated by the fractograph of Figure 13. Ductile dimples are noted to initiate from widely dispersed small particles (indicated by the arrows) that had exhibited a brittle cleavage fracture. These particles were the same intermetallic compounds noted in the microscopic study of the weld metal. The dispersion of the intermetallic particles in the area shown in Figure 13 is several orders of magnitude greater than that of the toe regions.

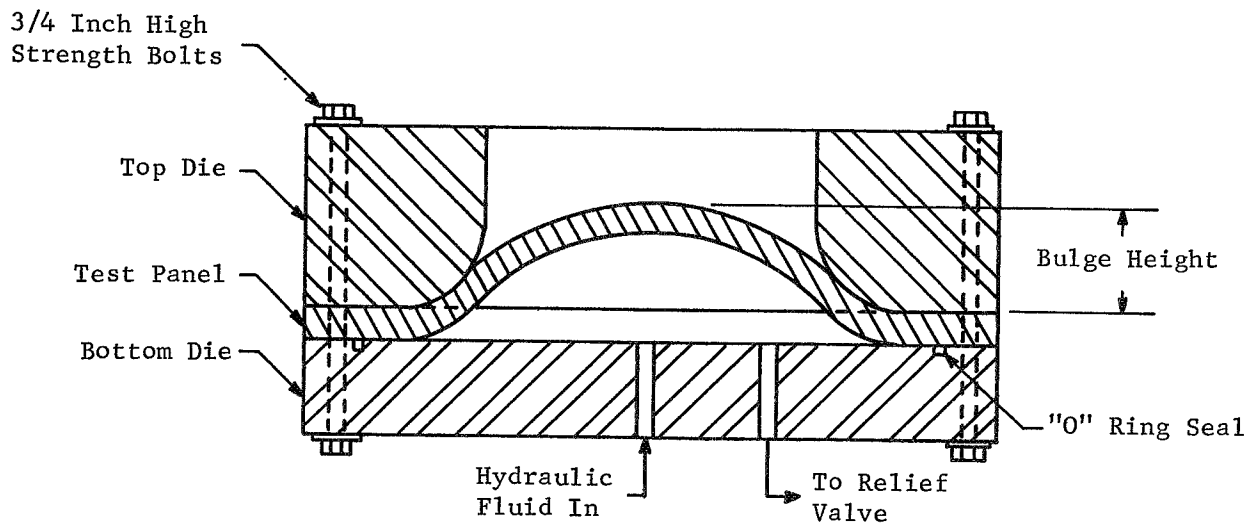


Figure 11, Cross Section of The Hydraulic Bulge Test Fixture

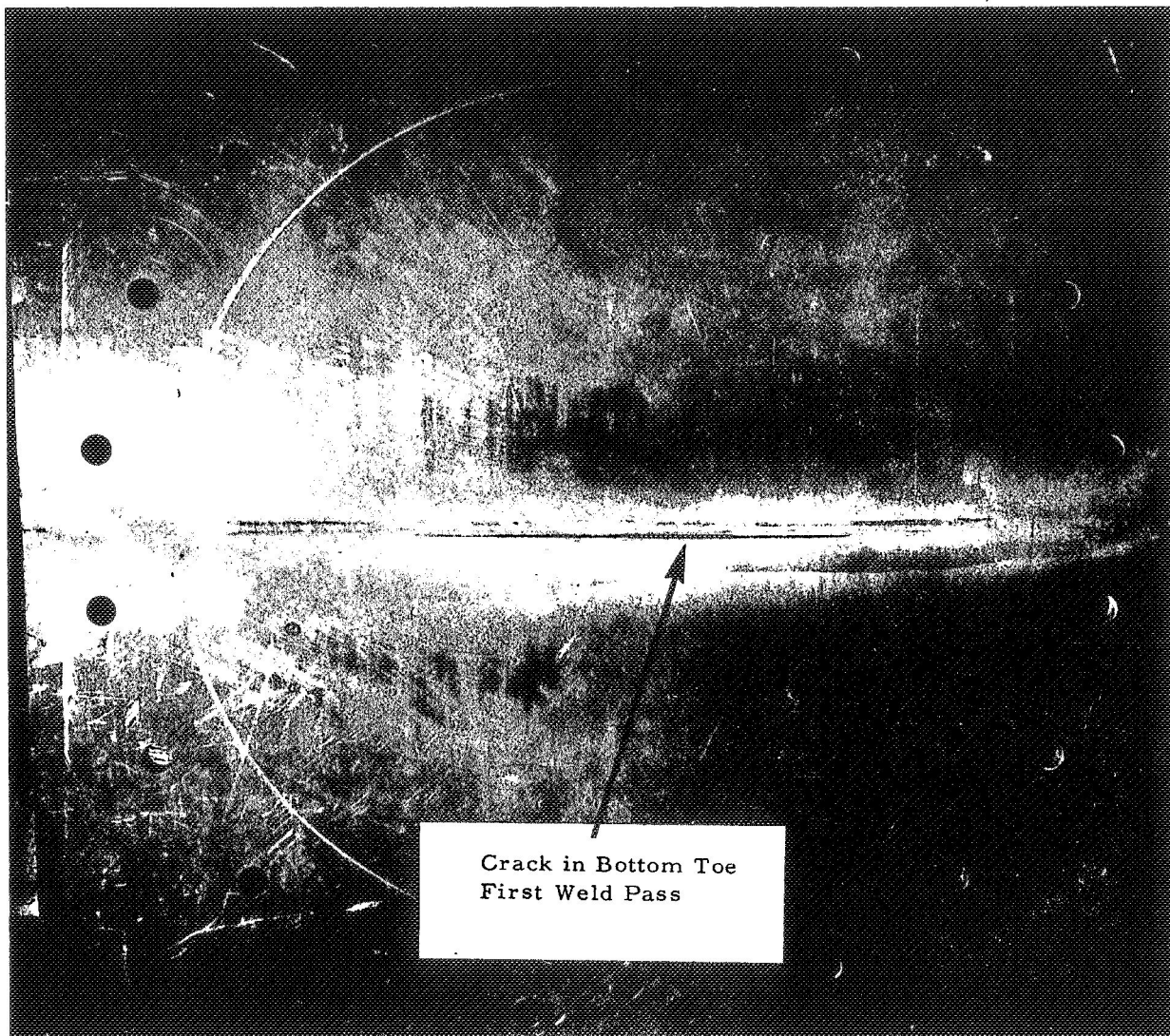


Figure 12, Fracture in a 3/4 Inch Thick Welded 2219-T87 Panel After Bulge Testing



Two-Stage Plastic-Carbon Replica

6000X

Figure 13. Electron Fractograph Showing Ductile Dimple Fracture in The Weld Metal. Arrows Indicate Origin of Dimples at Intermetallic Precipitate



## Conclusions

The conclusions which may be drawn from the work reported are the following:

1. Because of the low weld deposit strength, strain is concentrated in the weld metal and weld transition region.
2. As a result of this fact yield strength measured at a total strain of 0.2 percent offset in a 2 inch gage length can be expected to be considerably higher than that required to produce gross plastic deformation in the weld region.
3. Yield strength to be used in design should be measured with an extensometer equal to the width of the weld or with a strain gage mounted in the weld metal.
4. The weld crown contributes to the strength of the weldment but intensifies the strain at the toe of the crown. Removal of the weld crown results in improved ductility and lower strength.
5. The metallurgical condition at the bottom toe of the weld is responsible for initiating failure. The influence of inter-metallic phases on ductility was established by placing fusion passes along each weld toe. Thus the geometrical stress concentration was maintained but the metallurgical condition was removed. This resulted in increased ductility.
6. Biaxial tests indicated interesting crack propagation effects. This test will be employed in future studies to determine the relative influence of materials and welding parameters on weld performance.

## DISCUSSION

Mr. Chyle: Who has a question?

Question: Has any work been done on longitudinal specimens?

Mr. Lenamond: No, we have not looked at longitudinal specimens, and I don't know that we will be looking at longitudinal specimens, just transverse.

Miss Brennecke: Is there any relation between properties and the length of your weld in the transverse specimen - actually the width of the specimen - versus the thickness? You had a ratio of 1 to 3 ( $\frac{1}{4}$  inch slice in  $\frac{3}{4}$  inch thickness). How would your properties differ if you had a longer length of weld in the specimen, for instance, a  $1\frac{1}{2}$  inch wide specimen resulting in a 2 to 1 ratio? We had in electron beam welds quite a variation in strength with width of specimen. Our specimens were slices  $\frac{1}{8}$ ,  $\frac{1}{4}$ , and  $\frac{1}{2}$  inch wide and as the width of the specimen increased, the strength increased. Let me say, we used these narrow specimens because the width of our welded block was only 6 inches, so we were rather limited in the type of specimen we could take. There, in EB welds, a relation was established between the width of the specimen and the properties developed. Now, for your TIG welds here, I am wondering what relation might exist and also how the specimen width-to-thickness ratio might affect the location of your failure? In our EB slices, we had failure diagonally across the weld similar to your TIG. Later on when we had wider specimens---it was particularly noticeable in the  $2\frac{3}{8}$  inch thickness---our failures occurred in the interface rather than diagonally across the weld. So, there would be a difference in the distribution of the strains with specimen geometry, wouldn't there?

Mr. Lenamond: Yes, there definitely would be a difference in the distribution, although, I think the magnitude would tend to follow just what we've shown here. Even though these things would vary in the weld deposit, the fusion zone, and the heat-affected base metal, I think the magnitude would hold true there.

Mr. Monroe: I think that what Hap was saying here is very important. The test specimen geometry certainly has a big effect on the strength and elongation that you get. Along that line, did you make any comparison, collect data from your bulge test, either elongation or some type of strength calculation that you could relate to your uniaxial data?

Mr. Lenamond: I might mention this. We spent a considerable amount of time in looking at the ultimate strength properties and the yield strength properties of the bulge tests, and we were not able to define the ultimate strength of the bulge test. However, we did look at the yield strength quite heavily. The data has been reduced, but we are not exactly content with what we found. We don't have enough data to correlate this with the uniaxial tensile specimens. I might mention here, our objective was to compare one type of joint configuration with the other on a maximum load type basis. Not necessarily on the mechanical properties, although we did look at the mechanical properties.



Mr. Chyle: You mentioned a Tukon hardness test. Was this micro-hardness testing?

Mr. Lenamond: Micro-hardness test, yes.

Mr. Chyle: Are there any other questions? Well, in behalf of our audience here, we want to thank you for a very fine presentation; the audience has also been very patient. We had a very strenuous program. We had seven speakers, and I'm sure you're ready now for a good meal. I'll turn it over to Mr. Orr.

Mr. Orr: This is going to be my shortest announcement. Let's eat. The buses are outside.

FILLER WIRE COMPARISON OF 2014-T6  
WELDED WITH 716 AND 4043 FILLER WIRES

By

J. G. Maciora

and

W. R. Hutchinson

THE MARTIN COMPANY  
ORLANDO, FLORIDA

## ABSTRACT

Over 500 specimens were prepared and tested to evaluate weldability, tensile strength, ductility and corrosion resistance of weldments made with 716 and 4043 filler materials. Superior results were obtained with 716 filler material with a slight decrease in ductility. Both filler materials met ABMA-R-27A radiographic requirements for Army Ordnance Ballistic Missile applications. Weldments made with 716 were as high as 12 percent stronger; crack sensitivity slightly superior; and corrosion resistance adequate in both instances. Continued use of 716 filler material is recommended for Pershing Missile applications with 4043 as a second choice.

## INTRODUCTION

During the transition period of the Pershing missile from its R & D to its industrial production concept, Martin-Orlando proposed, and the Army Ballistic Missile Agency approved, a design change from riveting to automatic precision fusion welding of the 1st and 2nd stage aft skirts (2014-T6 aluminum alloy .090-.112 inch thick) and the guidance and control base and cover assemblies (.063 inch thick). The ABMA-PD-W-45W welding specification was designated as applicable. It required the use of FS-RAL-716 filler wire for the welding of the 2014-T6 aluminum alloy sheet and forged-ring assemblies.

To further insure excellent welding reliability, ABMA designated Class II, or better, radiographic requirements, as listed in ABMA-PD-R-27A. During initial welding some difficulty was experienced with porosity to meet these requirements with assemblies fabricated with the help of commercially available 716 filler wires. To eliminate this difficulty, one of the major causes was eliminated by procuring shaved 716 filler wire. This approach improved the radiographic quality of the welded assemblies. The filler wire, available only on special order, removed surface impurities which would result in weldment porosity. Shaved filler wire appreciably reduced porosity and resultant costly rework which decreased the mechanical properties of the assemblies.

ABMA was requested to permit the use of commercially available high-quality 4043 filler wire (Reference 2-7). Considerable research and development in welding the 2014-T6 aluminum alloy with the help of this filler wire had been done by Martin-Baltimore on the Titan missile program (Reference 1). A poor quality shipment of the 716 filler wire could seriously affect production schedules since only one vendor can supply it to desired quality standards. A second source supplier is highly desirable to prevent procurement difficulties. Efforts have been made to secure a second source for the 716 shaved filler wire. However, no vendor will accept orders for less than 1,000 lbs. and still the quality of the wire would be questionable.

A formal proposal for filler wire evaluation was submitted to ABMA by Martin-Orlando in July, 1961 (Reference 8). This proposal was approved by ABMA in August, 1961 (Reference 9).

The objectives of this investigation were to:

- (a) compile data on the FS-RAL-43 filler wire;
- (b) determine under production conditions, the cleanliness of filler wires concerned, and the reduction of inclusions and rework;
- (c) recommend a filler wire, or wires, that would produce high-quality Pershing weldments with excellent reliability at minimum cost;
- (d) determine the crack susceptibility of the filler wires.

## DESCRIPTION OF WORK

### Materials

The materials used in the investigations included:

- 1. Alclad aluminum Alloy Sheet, 2014-T6, Specification QQA-225a (Federal)
- 2. Aluminum Welding Filler Rod, FS-RAL-716 & 43, Specification QQR-566 (Federal)
- 3. Argon Shielding Gas, Specification MIL-A-4144 (USAF)

The aluminum alloy sheet used in this investigation consisted of various thicknesses of alclad 2014-T6 material that was solution heat-treated and artificially aged to meet the requirements of QQ-A-225a.

The aluminum alloy welding filler materials used to weld the test panels were drawn to the 1/16-inch diameter to meet QQ-R-566 requirements. The FS-RAL-716 and FS-RAL-43 welding filler wires were shaved free of impurities prior to the final drawing operation. Both filler wires were metallurgically bright and shiny. As a special precaution the filler material was kept clean of both dirt and moisture by packaging in accordance with military requirements. The chemical requirements of the filler materials are listed in Table I.

The argon shielding gas used during the welding operation was of high-purity (99.99 percent), and low dew-point (-150°F) to meet the MIL-A-4144 requirements. Gas was stored in a permanent cascade system.

Spectrographic analyses were made on both the base-metal and filler materials. All analyses were within the specification requirements.

## WELDING PROCEDURES

### Joint Preparation

#### Test Panels

The test panels were sheared transversely to the longitudinal rolling direction of the 4 x 12-foot sheet material and wiped clean with isopropyl alcohol. The sheared weld edge was filed flat with a vixon file (perpendicular to the surface and its edges were slightly "broken" (15°) with the same tool. The test panels

were again wiped with a clean paper towel and clean isopropyl alcohol. The test panels were then butted tightly together in a simple straight butt-joint and welded in the laboratory stake fixture in accordance with welding parameters in Table II.

#### The Reeves Restrained Sheet Crack - Sensitivity Test Panels

Panels 4 inches wide by 12 inches long were made with a single level, 80° included angle butt-joint with a 1/32-inch land, and a .035-inch root opening. Welding edges were cleaned as noted above, using an isopropyl alcohol wipe prior to and after beveling. Panels were clamped securely and completely sequence fillet-welded to a 3/4 inch grooved aluminum-backing plate.

#### Back-up Grooves

##### Test Panels

The back-up bars used to weld the .063 and .112-inch sheet test panels were made from low-carbon steel with a modified round-bottom groove.

##### Reeves Test

The Reeves test restraining plate had a groove machined 3/8-inch in diameter, .085-inch deep, and 12-inches long.

#### Welding Conditions

##### Test Panels

Welding prerequisites used to join the test panels, with the exception of the Reeves test specimens, were established for the automatic tungsten-inert-arc process. The energy-input of 5,700 joules/inch was used for .063-inch thick material as on the G & C assemblies. The .112-inch thick sheet, duplicating the aft skirt assemblies, was welded with an energy-input of 14,700 joules/inch. The conditions are shown in Table II.

##### Reeves Test

This test specimen was butted, and the automatic tungsten-inert-arc process was used with an energy-input of 14,700 joules/inch which was the same as used for the .112-inch sheet material previously mentioned.

#### TEST SPECIMEN PREPARATION

The test panels were first welded in groups of five, with one filler material, and then alternated to the other until twenty panels were completed for each type of filler wire.

This was performed on .063 and .112-inch thicknesses, duplicating the minimum and maximum thickness used on the Pershing production assemblies. Next, the test panels were radiographed and marked as Class II or better, of the ABMA-PD-R27A specification. The test panels were aged for at least ten days at room temperature before they were used to make the test specimens. The only exception was the Reeves restrained test specimen which was specially made to check the crack-sensitivity of the filler materials.

The detailed procedures for specimen removal and configuration of the specimen were:

Table I. Chemistry Specifications For Filler And Sheet Materials.

Filler Or Sheet Material	Cu(a)	Mg(a)	Mn(a)	Cr(a)	Si	Fe(a)	Zn(a)	Ti(a)	Al	Others, Each	(a) Others, Total
716(b)	$\frac{3.3}{4.7}$	0.15	0.15	0.15	$\frac{9.3}{10.7}$	0.8	0.2	---	Remainder	0.05	0.15
4043(b)	0.3	0.05	0.3	---	$\frac{4.5}{6.0}$	0.8	0.3	0.2	Remainder	0.05	0.15
2014(c) (Core Alloy)	$\frac{3.9}{5.0}$	$\frac{0.20}{0.80}$	$\frac{0.40}{1.20}$	0.10	$\frac{0.50}{1.2}$	1.0	0.25	0.15	Remainder	0.05	0.15
(a) Maximum Allowable Content											
(b) Specification QQ-R-566											
(c) Specification QQ-A-255a											

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Table II. Welding Conditions For Joining 0.063 - And 0.112-inch Thick 2014-T6 Alclad Aluminum Alloy Sheet Material.

Material Thickness, inches	Arc Aperage, amps	Arc Voltage, volts	Arc Length inch	Carriage Travel, inches/min.	Wire Feed Speed, inches/min.	Tungsten type	Tungsten Dia., inches	Argon Gas Flow, CFH	Diameter Filler wire, Inches
0.063	127	11.0	0.074	15	28	Zirconia	3/16	12	1/16
0.112	245	15.5	0.250	11	88	Zirconia	1/4	25	1/16

## Transverse-tensile Specimens

The transverse-tensile specimens were removed transverse to the welding direction and parallel to the direction of rolling as shown in Figure 1. The dimensions of these specimens are given in Figure 2 and 3.

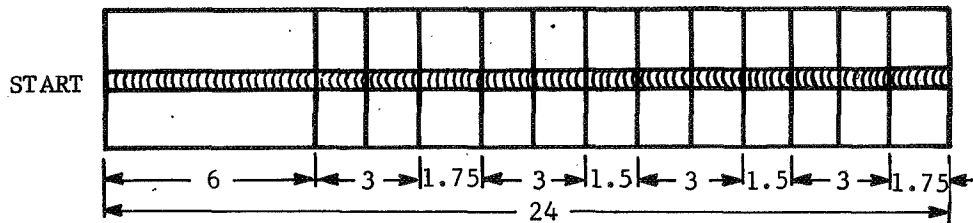


Figure 1. Transverse Welded Tensile Specimen Location on 0.063 and 0.112 Inch Test Panels

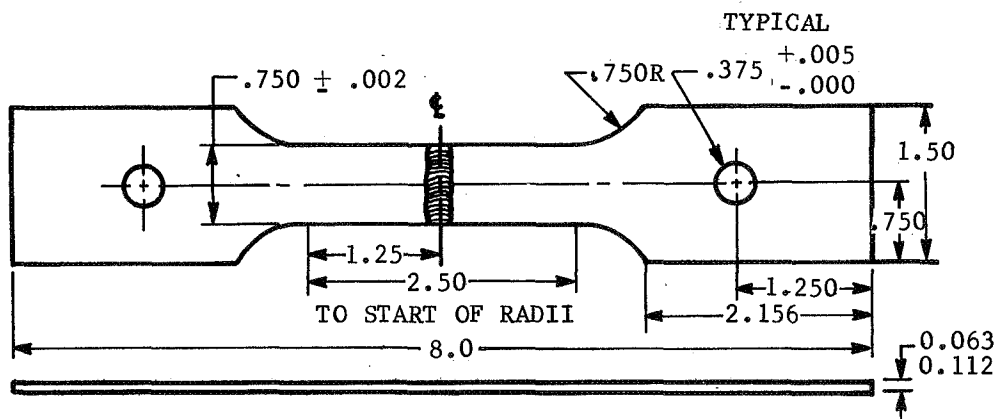


Figure 2. Reduced-section Welded Tensile Specimen

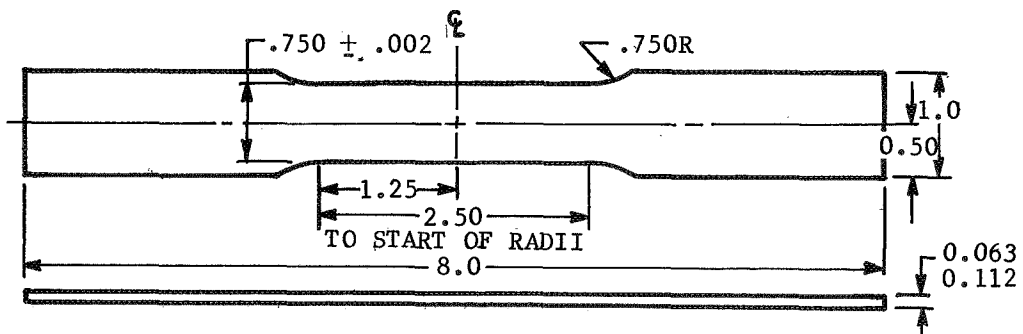


Figure 3. Base Metal Tensile Specimen.

### Base-metal Tensile Specimens

The location of the base-metal specimen removal location is shown in Figures 4 and 5.

### Transverse-bend Specimens

The locations of the transverse-bend specimens are shown in Figure 6. Bend specimens were 8-inches long by 1-inch wide for .063-inch material, and 1.5-inch wide for the .112-inch thick material. Weld length was 1-inch and 1.5-inch respectively.

### Longitudinal-bend Specimens

The longitudinal-bend specimens were removed from the welded panels, as described in Figure 7. The dimensions of the specimens were the same as above. Weld bead ran the full length of the specimen.

### Reeves Restrained Sheet Crack-sensitivity Specimens

The test panels were prepared, as previously mentioned under joint preparation, butted, and clamped to a 3/4-inch thick restraining plate. The butted sheets were then sequence-fillet welded to the 3/4-inch thick restraining plate and allowed to cool down to room temperature. The restrained plate was then ready for the actual weld test. This test specimen is shown in Figure 8.

### Naval Research Laboratory Sheet Bulge Specimen

These bulge specimens were cut from the start, center and end of the butt-welded panels. Figure 9 shows the locations of the specimens and the areas from which they were removed.

## TESTING METHODS

In order to fully evaluate the advantages and disadvantages of the 716 filler material over the 4043 filler material, it was necessary to determine the tensile stresses, yield stresses, and elongation by testing transverse-tensile specimens. Further evaluation was made by testing transverse and longitudinal-bend specimens, the Reeves restrained sheet crack-sensitivity test as well as the Naval Research Laboratory sheet bulge specimens. The testing procedures for each type of specimen used in this investigation are described below.

### Transverse-tensile Tests

The Weidman-Baldwin 60,000 lbs universal testing machine was used. For room temperature testing, the 12,000 lbs scale was used. Tensile specimens were loaded with the help of center pins. The maximum loading rate was 0.005-inch per-inch-per-minute, for all specimens with one exception. Room temperature tests were stopped at the yield strength. Extensometer was removed and balance of the test pulled at a rate not to exceed 0.05-inch per-inch-per-minute. For elevated temperature testing at 600°F, the 2,400 lbs scale was used. Loading rate was the same as used in room temperature testing. To obtain the 600°F temperature, quartz heating lamps were used in a clam-shell oven. The



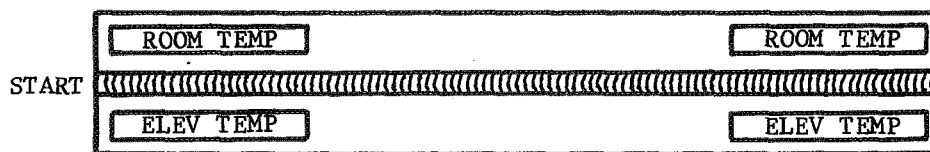


Figure 4. 0.063-inch Base Metal Specimen Location

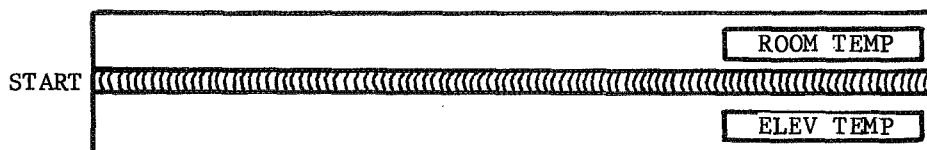


Figure 5. 0.112-inch Base Metal Specimen Location

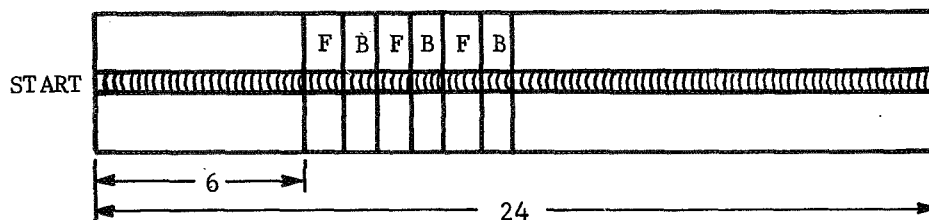


Figure 6. Transverse-bend Specimen Location in 0.063 and 0.112

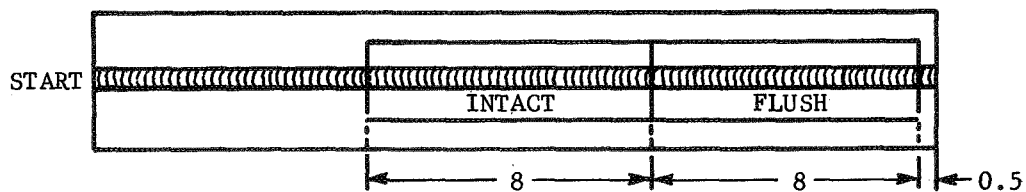


Figure 7. Longitudinal-bend Specimen Location in 0.63 and 0.112 Panels

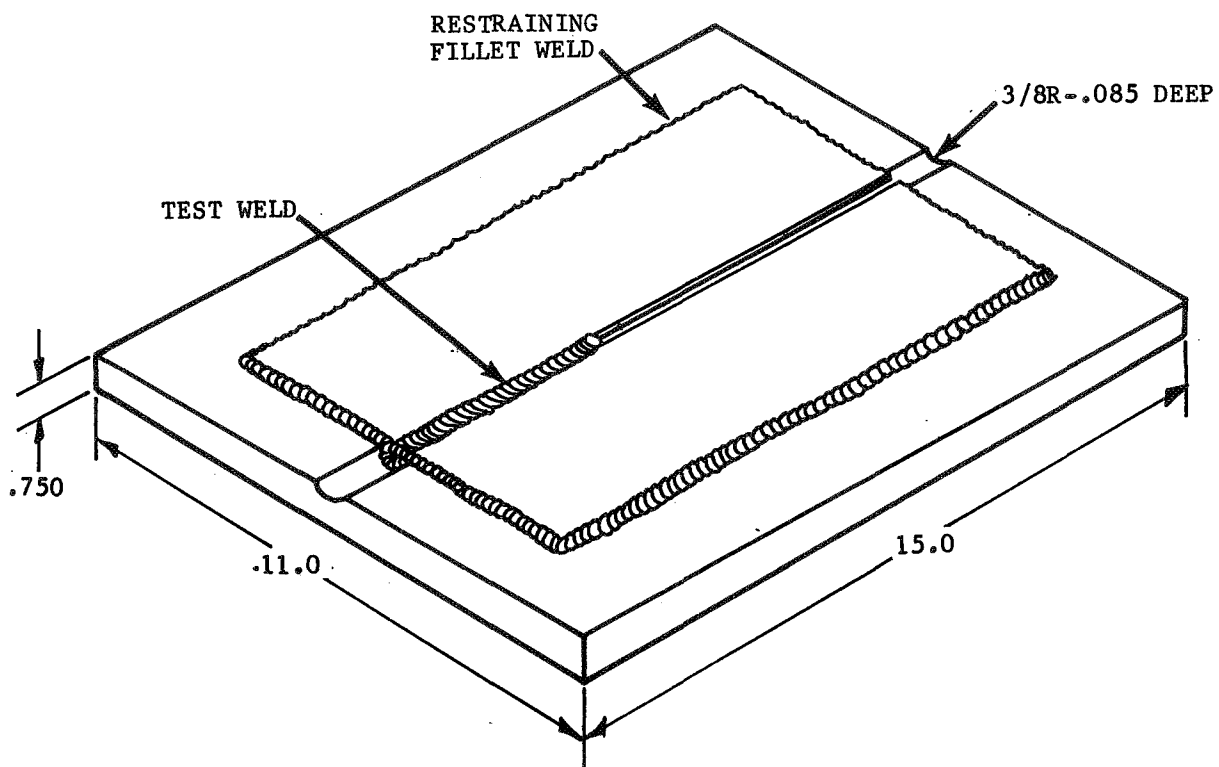


Figure 8. Reeves Restrained Sheet Crack-sensitivity Test Specimen

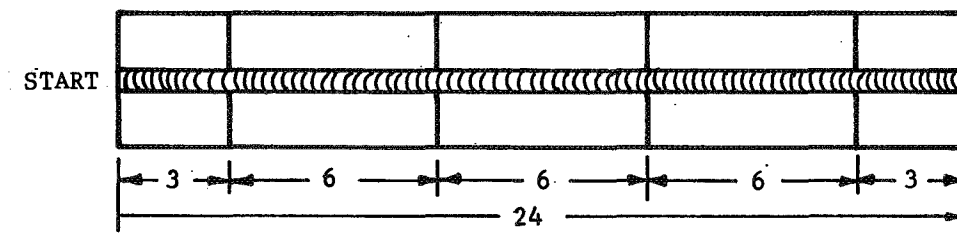


Figure 9. Naval Research Laboratory Sheet Bulge Specimen Location

test specimens were held at this level for 2 minutes. The reduced section was controlled to within  $\pm 5^{\circ}\text{F}$  with the aid of an Iron-Constantin thermocouple spot-welded to each specimen at the center of the gage length.

#### Transverse and Longitudinal Free-Bend Tests

The initial bending of these specimens was accomplished by using a double 1/2-inch radiused plunger which straddled the weld on either side by 3/4-inch. After the initial bends, the test specimen was placed as a strut in a vise and bent until failure was noticed in the outside bent surface, or until the specimen was bent double. Both face and root-bends were made. Specimens were examined visually for cracks.

#### Transverse Guided-bend Tests

The testing method consisted of bending the specimen in a bend-jig using a 1/2-inch diameter plunger for 0.063-inch material. The specimens were bent with both the face and root in tension. No 0.112-inch specimens were tested.

#### Corrosion Salt-Spray Test

A control panel of 0.063-inch thick alclad 2014-T6 sheet materials and panels welded with 716 and 4043 filler materials were subjected to a salt-spray corrosive medium according to the procedure outlined in Test Method 811-1, Federal Test Method Standard Number 151a. The test panels were supported in the salt spray cabinet at a  $15^{\circ}$  angle from the vertical and parallel to the corrosive medium fog flow. The face of the weld was upward and subjected to the full effect of the corrosive medium. The corrosive medium was a 5 percent solution of sodium-chloride at  $95^{\circ}\text{F}$  with a humidity control of 95-98 percent. The panels were exposed for 288 hours. After removal the panels were cleaned and sectioned for micro-examination for corrosive penetration.

#### Reeves Restrained Sheet Crack-sensitivity Test

This test was performed to evaluate the crack-sensitivity of the two filler materials considered. Fillet-welding of the test panels to the restraining plate prevents the panels from expanding or contracting during final test butt weld operation.

The restrained plate was positioned for a flat butt-weldment and welded with the parameters normally used for production assemblies. The only change involved was the filler-material speed which was reduced to produce a slightly concave bead to accentuate cracking.\* When completed, the weldment was permitted to cool to room temperature. The test plate was then examined visually for cracks. The specimen was carefully removed from the heavy restraining plate and radiographed. When radiograms showed no cracks, the section was removed from its maximum restrain point (1 inch from the end), polished on fine

\*Maximum restraint is obtained as the flat butt-weldment nears completion. Usually, cracking will occur if the filler material is sensitive to root-bend cracking which duplicates actual production applications.

emery paper, etched in Keller's etchant, and examined at 50 X to insure that micro-cracking was not overlooked.

#### Naval Research Laboratory Sheet Bulge Test

Because of the complexities involved in welding, it is not possible to evaluate fully all of the weld-zone regions by conventional crack-propagation test techniques. For this reason, the Naval Research Laboratory Sheet Bulge Test was chosen for its simplicity and inexpensive features. The test employs rubber as a non-compressible fluid medium for transmitting the force of an impact blow on 6 inch sq specimens. The test is conducted in uniquely designed equipment free of complicated fixtures or gripping devices. The most significant aspect of this test is that of demonstrating potentially weak or brittle failure paths in a welded assembly. They are particularly effective in evaluating the heat-affected and fusion zones (Reference 10). The impact blow obtained with the 300 lbs weight dropping from an eight-foot height, and the open-die used on all specimens duplicate the high stress rates encountered by the Pershing during field maneuvering. Total loading, in all instances, far exceeded anticipated ground handling conditions. The operating conditions during the drop test involved freezing-temperature at minus 65°F, normal-temperature at 78°F, and hot-temperature at plus 160°F.

### DISCUSSION OF RESULTS

#### Weld Quality Tests

For the test panels (0.063-inch and 0.112-inch thick 2014-T6 materials, welded with 716 and 4043 filler materials) the radiographic results showed that the weld metal quality was essentially equal (Table III). However, micrographic examination at 7x revealed that the 4043 weld metal was cleaner with much less microporosity. Typical examples of the microporosity are shown in Figures 10 and 11. All the test panels met the Class II radiographic quality standards, or better. The fact that the commercially available vacuum-packed, high-quality, shaved 4043 filler material shows less microporosity may be due to lower occluded or dissolved gas content due to vacuum packaging.

#### Tensile Tests

The transverse-tensile specimens used in the investigation gave the mechanical properties of welds prepared with special high-purity shaved 716 filler material, and commercially available and vacuum-packed high-quality shaved 4043 filler material. These tests were made at room- and elevated- temperatures (78° and 600°F respectively).

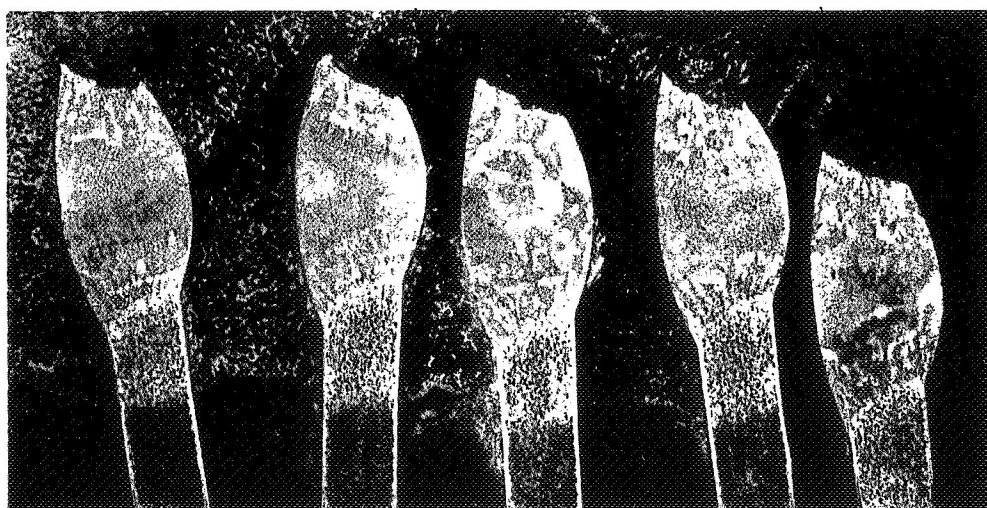
Based on the average strength obtained for the unwelded sheet, a joint efficiency was calculated for each weld condition. This value, expressed in percent of the unwelded sheet ultimate and yield strength, is shown in Table IV for .063-inch material and in Table V for .112-inch material.



Neg. #0634

(7x)

**Figure 10.** Macrograph of 716 Welded 0.063-inch Transverse Tensile Specimens Etched to Show the Macroporosity in the 716 Weld Metal-Special High-Purity Shaved Filler Material. Keller's Etchant



Neg. #0634

(7x)

**Figure 11.** Macrograph of 4043 Welded 0.063-inch Transverse Tensile Specimens Etched to Show the Smaller Amount of Macroporosity in the 4043 Weld Metal (Commercially Available High-Quality Shaved, Vacuum-packed Filler Material) Keller's Etchant

Table III. Quality Test Panels for 0.063- and 0.112- Inch Thick  
2014-T6 Alclad Aluminum Sheet Material.

Thicknesses, inches	Filler Material Used	Total Number of Panels Welded	Number of Panels Class I	Number of Panels Class I-II	Number of Panels Class II
0.063	716	40	35	---	5
0.063	4043	40	33	3	4
0.112	716	20	16	---	4
0.112	4043	20	16	---	4

Table IV. Weld Strength Expressed As A Percent of Sheet Strength  
for .063-Inch Material.

<u>Filler Material</u>	<u>Cond of Bead</u>	<u>Temp °F</u>	<u>FTU % Of Sheet Str.</u>	<u>FTY % Of Sheet Str.</u>
--	--	RT	100.0	100.0
4043	Intact	RT	78.7	66.0
4043	Flush	RT	57.9	53.5
716	Intact	RT	79.0	69.1
716	Flush	RT	64.0	62.5
4043	Intact	600	90.4	98.0
4043	Flush	600	83.7	87.3
716	Intact	600	92.3	95.8
716	Flush	600	94.0	95.8
--	--	600	100.0	100.0

Table V. Weld Strength Expressed As A Percent of Sheet Strength  
for .112-Inch Material.

<u>Filler Material</u>	<u>Cond of Bead</u>	<u>Temp OF</u>	<u>FTU % Of Sheet Str.</u>	<u>FTY % Of Sheet Str.</u>
--	--	RT	100.0	100.0
4043	Flush	RT	56.1	47.8
4043	Intact	RT	81.0	61.2
716	Intact	RT	84.2	67.3
716	Flush	RT	60.0	54.7
4043	Intact	600	86.0	85.7
4043	Flush	600	73.5	73.5
716	Intact	600	84.1	85.7
716	Flush	600	83.7	80.7
-	-	600	100.0	100.0

The average, high and low values for each group of specimens are shown in Tables VI and VII. Original data is continued in Tables VIII to XXVII. The removal effect of the bead reinforcement and temperatures is shown in Figure 12. Figure 12 and tables XXVIII thru XXXIII were prepared by Materials Engineering.

Table VI. High, Low, and Average Strength of Welded .063-Inch 2014-T6 Aluminum.

<u>Filler Material</u>	<u>Cond of Bead</u>	<u>Temp OF</u>	<u>FTU - KSI</u>			<u>FTY - KSI</u>		
			<u>Hi</u>	<u>Lo</u>	<u>Av</u>	<u>Hi</u>	<u>Lo</u>	<u>Ave</u>
-- **	--	RT	70.9	68.2	68.8	60.7	59.3	59.9
4043	Intact	RT	55.7	52.0	54.1	40.8	38.5	39.7
4043	Flush	RT	42.8	37.3	39.8	34.0	30.8	32.0
716	Intact	RT	55.7	51.7	54.3	42.4	40.0	41.4
716	Flush	RT	45.2	41.4	44.0	38.2	36.1	37.4
4043	Intact	600	16.9	14.2	14.9	14.6	12.0	13.7
4043	Flush	600	15.1	13.0	13.8	13.5	11.6	12.2
716	Intact	600	16.4	14.5	15.2	14.5	12.0	13.4
716	Flush	600	17.4	14.2	15.5	14.8	12.3	13.4
---**	--	600	18.0	15.6	16.5	15.6	12.3	14.0

Table VII. High, Low, and Average Strength of Welded .112-Inch Clad 2014-T6 Aluminum.

Filler Material	Cond of Bead	Temp °F	FTU - KSI			FTY - KSI		
			Hi	Lo	Av	Hi	Lo	Av
---	---	RT	74.7	70.3	72.2	65.4	61.9	63.8
4043	Flush	RT	42.7	38.5	40.5	33.9	27.6	30.5
4043	Intact	RT	59.8	57.1	58.4	40.1	37.8	39.0
716	Intact	RT	61.5	60.2	60.7	43.7	41.5	42.9
716	Flush	RT	44.8	41.2	43.3	35.7	34.1	34.9
4043	Intact	600	19.7	16.0	17.8	17.1	13.8	15.5
4043	Flush	600	16.9	14.0	15.2	15.6	12.2	13.3
716	Intact	600	20.4	14.7	17.4	16.7	13.4	15.5
716	Intact	600	18.9	16.0	17.3	15.8	13.4	14.6
---	---	600	24.0	19.2	20.7	19.9	17.2	18.1

\*\* Unwelded Transverse sheet strength

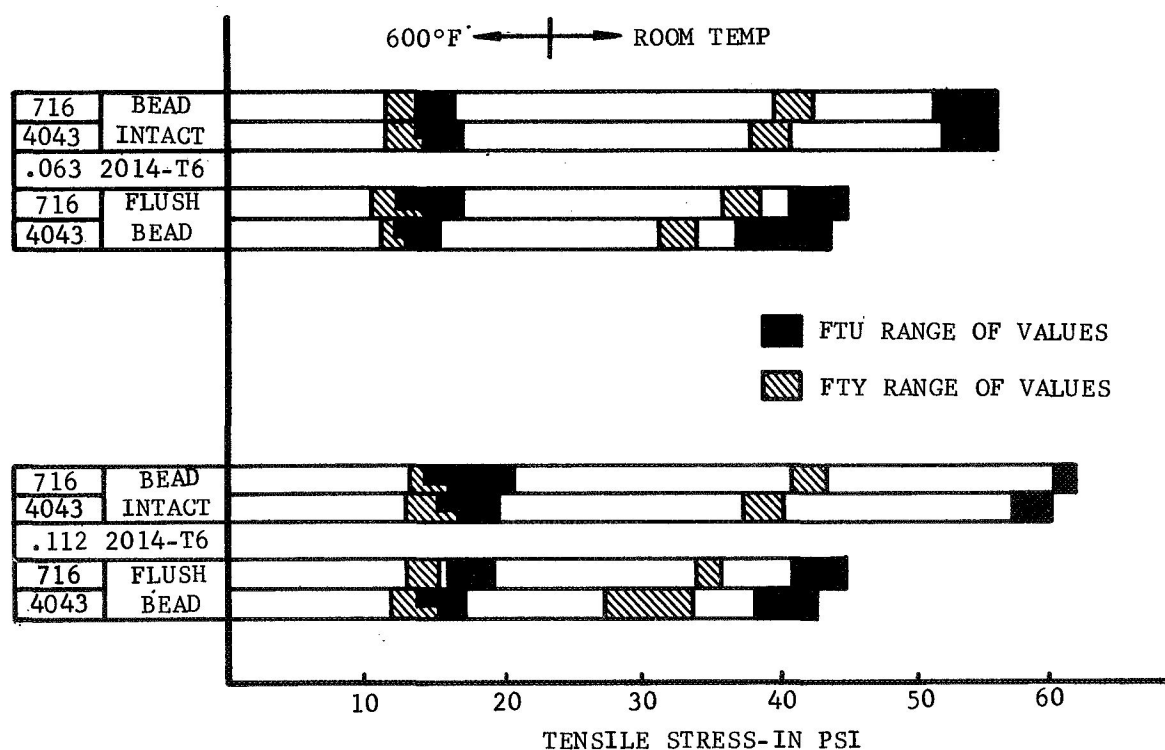


Figure 12. Comparison of the Ultimate and Yield Tensile Strength of Fusion-welded 2014-T6 Using 4043 and 716 Filler Material



Table VIII. Fusion Welded .063-Inch 2014-T6 Using 4043 Filler  
Bead Intact Tested At Room Temperature

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
43R - 1	40,800	52,900	8.0	3.5	2.0	WFZ
- 2	38,600	52,000	8.0	4.0	2.0	WFZ
- 3	---	---	-	-	-	WFZ
- 4	38,500	53,300	8.0	4.0	2.0	WFZ
- 5	40,100	53,800	8.0	4.0	2.5	WFZ
- 6	40,100	53,800	8.0	3.5	2.5	WFZ
- 7	39,400	54,900	10.0	4.0	2.5	WFZ
- 8	40,000	55,300	10.0	5.0	2.0	WFZ
- 9	39,600	54,000	10.0	4.0	2.0	WFZ
- 10	39,000	54,600	10.0	5.0	2.0	WFZ
- 11	39,800	55,100	10.0	4.0	2.0	WFZ
- 12	40,200	53,100	8.0	4.0	2.0	WFZ
- 13	39,700	52,700	8.0	4.0	2.0	WFZ
- 14	39,700	54,400	8.0	4.0	2.0	WFZ
- 15	39,100	52,700	8.0	4.0	2.0	WFZ
- 16	39,400	55,000	10.0	4.0	2.0	WFZ
- 17	40,300	55,700	10.0	4.0	2.0	WFZ
- 18	40,400	54,900	10.0	5.0	2.5	WFZ
- 19	40,300	54,500	8.0	4.0	2.0	WFZ
- 20	39,600	55,100	10.0	5.0	2.5	WFZ

WFZ - Weld Fusion Zone

Table IX. Fusion Welded .063-Inch 2014-T6 Using 716 Filler  
Bead Intact Tested at Room Temperature.

Specimen No	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			<u>1/2"</u>	<u>1"</u>	<u>2"</u>	
716-R - 1	41,900	55,500	8.0	4.0	2.0	W
- 2	41,300	54,400	9.0	4.0	2.0	W
- 3	40,400	53,800	8.0	4.0	2.0	W
- 4	41,800	55,700	8.0	4.5	2.0	W
- 5	42,200	52,600	8.0	4.0	2.0	W
- 6	42,400	53,600	8.0	4.0	2.0	W
- 7	41,800	53,700	8.0	4.0	2.0	W
- 8	40,900	55,700	8.5	4.0	2.0	W
- 9	41,400	54,100	8.0	4.0	2.0	W
- 10	41,600	54,700	8.0	4.0	2.0	W
- 11	41,300	54,600	8.0	4.0	2.0	W
- 12	40,500	54,400	8.0	4.0	2.0	W
- 13	41,500	51,700	8.0	4.0	2.0	W
- 14	41,700	55,000	8.0	4.0	2.0	W
- 15	40,900	55,000	8.0	4.0	2.0	W
- 16	40,000	53,100	8.0	4.0	2.0	W
- 17	41,600	55,200	8.0	4.0	2.0	W
- 18	41,800	54,900	8.0	4.0	2.0	W
- 19	41,800	55,100	8.0	4.0	2.0	WFZ
- 20	41,000	52,500	8.0	4.0	2.0	W

WFZ - Weld Fusion Zone

Table X. Fusion Welded .063-Inch 2014-T6 Using 4043 Filler  
Flush Bead Tested at Room Temperature ,

Specimen No	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
43-R - 1	32,800	40,600	4.0	2.0	1.0	W
- 2	31,800	39,700	5.0	2.5	1.5	W
- 3	32,100	37,300	5.0	2.0	1.0	W
- 4	31,500	39,100	5.0	3.0	1.5	W
- 5	32,000	39,900	6.0	3.0	1.7	W
- 6	32,400	41,400	8.0	3.0	1.7	W
- 7	31,400	38,700	5.0	3.0	1.5	W
- 8	31,700	38,900	7.0	3.0	1.7	W
- 9	32,600	38,400	4.0	2.0	.5	W
- 10	30,800	39,100	5.0	2.0	1.0	W
- 11	31,600	41,000	7.0	3.0	1.5	W
- 12	32,300	42,000	7.0	4.0	2.5	W
- 13	32,700	41,100	7.0	3.5	2.2	W
- 14	34,000	42,800	6.0	3.5	1.7	W
- 15	31,200	38,600	5.0	3.0	1.5	W
- 16	32,600	40,100	6.0	3.5	2.2	W
- 17	31,600	38,700	4.0	3.5	2.0	W
- 18	31,000	39,100	7.0	3.5	2.2	W
- 19	31,900	40,400	7.0	3.5	2.2	W
- 20	32,000	39,400	5.0	3.0	1.2	W

Table XI. Fusion Welded .063-Inch 2014-T6 Using 716 Filler  
Flush Bead Tested At Room Temperature.

Specimen No.	Yield Stress Psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1108 - 1RF	37,300	43,300	6.0	2.0	2.0	W
- 2RF	38,100	43,400	6.0	2.0	1.5	W
- 3RF	37,400	43,900	6.0	3.0	2.0	W
- 4RF	36,100	44,400	6.0	3.0	2.0	W
1109 - 5RF	36,400	43,500	6.0	3.0	2.0	W
1109 - 6RF	37,100	45,200	6.0	3.0	2.0	W
- 7RF	37,500	43,400	6.0	3.0	2.0	W
- 8RF	36,600	44,000	6.0	3.0	2.0	W
1106 - 9RF	37,200	44,400	6.0	3.0	2.0	W
- 10RF	36,700	43,500	6.0	3.0	1.5	W
1106 - 11RF	37,900	44,300	6.0	3.0	2.0	W
- 12RF	38,100	43,900	6.0	3.0	1.5	W
1107 - 13RF	37,700	44,000	6.0	3.0	1.5	W
- 14RF	37,900	44,600	6.0	3.0	1.5	W
- 15RF	38,000	44,700	6.0	3.0	1.5	WFZ
1107 - 16RF	38,200	44,800	6.0	3.0	1.5	W
1108 - 17RF	37,500	44,300	6.0	3.0	1.5	W
- 18RF	37,500	44,900	6.0	3.0	1.5	W
- 19RF	37,800	41,400	6.0	3.0	1.5	W
- 20RF	37,000	44,700	6.0	3.0	1.5	W

WFZ - Weld Fusion Zone

Table XII. Fusion Welded .063-Inch 2014-T6 Using 4043 Filler  
Bead Intact Tested at 600°F.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1110 - 1H	13,200	14,500	12.0	8.0	4.5	WFZ
- 2H	13,700	15,600	8.0	6.0	3.0	WFZ
- 3H	13,000	14,800	8.0	6.0	3.0	WFZ
- 4H	13,700	15,500	8.0	6.0	3.0	WFZ
1104 - 5H	----	----	---	---	---	---
- 6H	13,000	14,600	8.0	6.0	3.0	WFZ
- 7H	13,000	15,200	10.0	5.0	4.0	WFZ
- 8H	----	----	---	---	---	---
1111 - 9H	13,300	15,300	10.0	6.0	4.0	WFZ
- 10H	13,100	15,000	10.0	6.0	3.5	WFZ
- 11H	13,400	15,700	10.0	6.0	3.5	WFZ
- 12H	13,100	15,000	10.0	6.0	3.5	WFZ
1112 - 13H	13,500	15,700	10.0	6.0	3.5	WFZ
- 14H	----	----	---	---	---	---
- 15H	12,000	14,200	10.0	6.0	3.5	WFZ
- 16H	14,600	16,500	10.0	6.0	3.5	WFZ
1113 - 17H	14,200	16,700	10.0	5.0	3.5	WFZ
- 18H	13,900	16,200	8.0	5.0	3.5	WFZ
- 19H	14,400	16,800	10.0	5.0	3.5	WFZ
- 20H	14,600	16,900	10.0	5.0	3.5	WFZ

WFZ - Heat Affected Zone

Table XIII. Fusion Welded .063-Inch 2014-T6 Using 716 Filler  
Bead Intact Tested at 600°F.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1089 - H1	14,500	16,300	10.0	5.0	3.0	WFZ
- H2	13,600	14,800	10.0	5.0	3.5	WFZ
- H3	12,500	14,700	10.0	5.0	3.5	WFZ
- H4	----	----	--	---	---	-----
108 - H5	14,000	16,100	10.0	5.0	3.0	WFZ
1085 - H6	13,100	14,900	10.0	5.0	3.0	WFZ
- H7	12,600	14,500	10.0	5.0	3.5	WFZ
- H8	12,900	15,000	10.0	5.0	3.5	WFZ
1088 - H9	----	----	--	---	---	-----
- H10	13,300	14,900	10.0	5.0	3.5	WFZ
- H11	12,700	14,500	10.0	5.0	3.5	WFZ
- H12	13,600	15,300	10.0	5.0	3.0	WFZ
1087 - H13	14,300	16,400	10.0	5.0	3.0	WFZ
- H14	----	---	--	---	---	-----
- H15	14,100	15,400	10.0	5.0	3.5	WFZ
- H16	14,100	15,100	10.0	5.0	3.0	WFZ
1086 - H17	13,000	14,600	10.0	5.0	3.5	WFZ
- H18	13,300	15,300	10.0	5.0	4.0	WFZ
- H19	12,000	14,500	10.0	7.0	5.5	WFZ
- H20	13,900	15,800	10.0	6.0	3.5	WFZ

WFZ - Heat Affected Zone

Table XIV. Fusion Welded .063-Inch 2014-T6 Using 716 Filler  
Flush Bead Tested at 600°F Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1108 - 1HF	12,500	16,300	12.0	7.0	4.5	WFZ
- 2HF	14,000	16,000	12.0	6.0	3.5	WFZ
- 3HF	13,800	15,800	12.0	6.0	3.5	WFZ
- 4HF	14,800	16,900	10.0	5.0	2.5	W
1109 - 5HF	----	----	----	---	---	---
1109 - 6HF	12,300	14,400	12.0	6.0	4.0	WFZ
- 7HF	12,500	14,500	12.0	6.0	4.5	WFZ
- 8HF	13,800	16,000	12.0	6.0	4.5	WFZ
1106 - 9HF	13,800	15,700	12.0	6.0	4.0	WFZ
- 10HF	13,900	15,900	12.0	6.0	4.0	WFZ
1106 - 11HF	14,000	16,000	8.0	4.0	2.5	W
- 12HF	13,100	14,900	4.0	6.0	3.5	WFZ
1107 - 13HF	13,700	15,900	10.0	5.0	3.0	W
- 14HF	13,100	15,300	10.0	6.0	3.0	W
- 15HF	13,200	15,400	10.0	6.0	3.0	W
1107 - 16HF	12,300	14,200	16.0	8.0	4.5	W
1097 - 17HF	14,100	16,200	10.0	5.0	3.5	W
- 18HF	13,500	15,600	10.0	5.0	3.5	WFZ
- 19HF	13,200	15,200	14.0	7.0	4.5	WFZ
- 20 HF	14,400	17,400	8.0	4.0	2.5	WFZ

WFZ - Heat Affected Zone

Table XV. Fusion Welded .063-Inch 2014-T6 Using 4043 Filler  
Flush Bead Tested at 600°F Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation- %			Type of Failure
			$\frac{1}{2}$ "	1	2"	
1110 - 1HF	11,800	13,400	16.0	8.0	4.5	W
- 2HF	11,900	13,00	12.0	6.0	3.0	W
- 3HF	12,100	13,500	18.0	9.0	4.5	W
- 4HF	12,400	14,100	18.0	9.0	4.5	W
1104 - 5HF	12,000	14,100	16.0	8.0	4.0	W
1104 - 6HF	12,500	14,000	12.0	6.0	3.0	W
- 7HF	11,800	13,300	12.0	6.0	3.0	W
- 8HF	----	---	---	---	---	-
1111 - 9HF	12,300	13,700	12.0	6.0	3.5	W
- 10HF	12,000	13,600	14.0	7.0	3.5	W
1111 - 11HF	12,100	13,900	24.0	12.0	6.0	W
- 12HF	---	---	----	---	---	-
1112 - 13HF	11,700	13,700	18.0	9.0	4.5	W
- 14 HF	12,500	13,800	18.0	9.0	4.5	W
- 15HF	13,500	14,900	12.0	6.0	3.5	W
1112 - 16HF	12,800	15,100	18.0	10.0	5.0	W
1113 - 17HF	12,600	14,300	18.0	10.0	5.0	W
- 18HF	12,100	13,900	16.0	8.0	4.0	W
- 19HF	12,200	14,000	16.0	8.0	4.5	W
- 20HF	11,600	13,200	18.0	8.0	4.5	W



Table XVI .063-Inch Clad 2014-T6 Transverse Sheet Strength  
Tested At Room Temperature,

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1142 - 1R	---	---	---	---	---	-
- 2R	60,300	68,600	---	---	12.0	-
1144 - 3R	59,300	68,400	---	---	12.0	-
- 4R	59,700	68,200	---	---	11.0	-
1143 - 5R	59,600	68,800	---	---	12.0	-
1143 - 6R	60,000	68,900	---	---	11.5	-
1141 - 7R	59,800	69,300	---	---	13.0	-
- 8R	59,900	68,700	---	---	12.0	-
1140 - 9R	60,000	68,900	---	---	12.0	-
- 10R	59,800	69,300	---	---	10.5	-
1147 - 11R	60,700	70,600	---	---	12.5	-
- 12R	60,700	70,900	---	---	14.0	-
1132 - 13R	60,700	69,900	---	---	13.5	-
- 14R	60,400	69,900	---	---	13.0	-
1134 - 15R	59,700	69,500	---	---	13.0	-
1134 - 16R	59,400	68,800	---	---	12.5	-
1133 - 17R	60,200	69,500	---	---	12.5	-
- 18R	59,400	69,000	---	---	12.0	-
1130 - 19R	59,800	69,900	---	---	12.0	-
- 20R	60,000	69,300	---	---	11.5	-

Table XVII .063-Inch Clad 2014-T6 Transverse Sheet Strength  
Tested at 600°F Temperature ,

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1142 - 1H	14,100	16,100	---	---	20.0	-
- 2H	14,000	16,400	---	---	11.5	-
1144 - 3H	13,800	15,700	---	---	14.5	-
- 4H	14,300	16,700	---	---	9.5	-
1143 - 5H	14,300	16,300	---	---	6.0	-
1143 - 6H	14,400	16,800	---	---	4.0	-
1141 - 7H	14,500	16,900	---	---	6.0	-
- 8H	12,800	15,600	---	---	7.0	-
1140 - 9H	---	---	---	---	---	-
- 10H	12,900	16,900	---	---	10.5	-
1147 - 11H	12,300	16,000	---	---	9.5	-
- 12H	14,400	16,800	---	---	3.5	-
1132 - 13H	13,800	15,800	---	---	11.5	-
- 14H	14,000	16,600	---	---	5.0	-
1134 - 15H	13,000	15,800	---	---	10.5	-
1134 - 16H	13,900	16,300	---	---	12.5	-
1133 - 17H	---	---	---	---	---	-
- 18H	15,300	17,600	---	---	4.0	-
1130 - 19H	15,400	17,600	---	---	11.5	-
- 20H	15,600	18,000	---	---	10.0	-

Table XVIII. Fusion Welded .112-Inch 2014-T6 Using 4043 Filler  
Bead Intact Tested at Room Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1172 - 1R	39,200	58,200	9.0	6.5	3.0	HAZ
- 2R	39,000	58,200	9.0	6.0	3.0	HAZ
- 3R	39,600	59,100	9.0	6.0	3.0	HAZ
- 4R	37,800	57,100	10.0	6.5	3.0	HAZ
1173 - 5R	38,600	57,600	10.0	5.5	3.0	HAZ
1173 - 6R	39,700	58,100	12.0	6.0	3.0	HAZ
- 7R	39,400	59,800	12.0	6.0	3.0	HAZ
- 8R	38,400	58,500	12.0	6.0	3.0	HAZ
1174 - 9R	38,400	57,800	12.0	6.0	3.0	HAZ
- 10R	40,100	59,400	12.0	6.0	3.0	HAZ

Table XIX. Fusion Welded .112-Inch 2014-T6 Using 716 Filler  
Bead Intact Tested at Room Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1177 - 1R	43,600	60,200	13.0	8.5	3.5	HAZ
- 2R	42,400	60,300	6.0	6.5	3.0	HAZ
- 3R	42,700	61,500	5.0	7.0	4.0	HAZ
- 4R	41,500	60,300	6.0	6.5	3.0	W
1179 - 5R	42,000	60,600	5.0	8.0	3.5	HAZ
- 6H	43,400	60,600	8.0	7.0	3.5	HAZ
- 7H	43,100	60,400	8.0	6.0	3.0	HAZ
- 8H	42,800	61,300	8.0	6.0	3.0	HAZ
1180 - 9H	43,700	60,600	8.0	6.0	3.0	HAZ
- 10H	43,600	61,100	8.0	6.0	3.0	HAZ

~~WAZ~~ - Weld Fusion Zone  
HAZ - Heat Affected Zone

Table XX. Fusion Welded .112-inch 2014-T6 Using 4043 Filler  
Flush Bead Tested at Room Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1182 - 1RF	30,000	42,700	9.0	4.0	2.5	W
- 2RF	29,700	41,300	8.0	4.0	2.5	W
- 3RF	28,100	40,700	10.0	5.5	2.5	W
- 4RF	29,500	41,300	10.0	4.5	2.5	W
1185 - 5RF	27,600	38,500	10.0	4.5	2.5	W
1185 - 6RF	33,900	40,200	8.0	4.0	2.5	W
- 7RF	32,800	40,400	8.0	4.0	2.5	W
- 8RF	33,300	38,900	8.0	4.0	2.5	W
1186 - 9RF	29,200	39,400	8.0	4.0	2.5	W
- 10RF	30,300	41,100	8.0	4.0	2.5	W

Table XXI. Fusion Welded .112-Inch 2014-T6 Using 716 Filler  
Flush Bead Tested at Room Temperature,

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1170 - 1RF	35,200	43,200	5.0	2.5	1.5	W
- 2RF	34,700	44,800	7.0	3.5	1.5	W
- 3RF	35,100	44,800	5.0	3.0	1.5	W
- 4RF	35,300	44,300	5.0	3.0	1.5	W
1169 - 5RF	34,100	43,300	5.0	3.0	1.5	W
1169 - 6HF	35,700	41,900	4.0	2.0	1.0	W
- 7HF	34,800	43,400	6.0	3.0	1.5	W
- 8HF	34,600	43,700	6.0	3.0	1.5	W
1168 - 9HF	34,600	43,600	6.0	3.0	1.5	W
- 10HF	34,600	41,200	6.0	3.0	1.5	W

Table XXII. Fusion Welded .112-Inch 2014-T6 Using 4043 Filler  
Bead Intact Tested at 600°F Temperature

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1172 - 1H	16,400	19,200	4.0	6.0	4.0	HAZ
- 2H	16,600	19,100	4.0	7.0	4.0	HAZ
- 3H	16,100	18,600	4.0	6.0	4.0	HAZ
- 4H	17,100	19,700	4.0	6.0	4.0	HAZ
1173 - 5H	15,900	18,400	4.0	6.0	4.0	HAZ
1173 - 6H	13,800	16,000	8.0	7.0	4.5	HAZ
- 7H	15,000	16,800	6.0	6.0	3.0	HAZ
- 8H	14,600	16,600	10.0	7.0	4.0	HAZ
1174 - 9H	14,500	16,600	10.0	7.0	5.0	HAZ
- 10H	15,100	17,100	10.0	7.0	5.0	HAZ

Table XXIII. Fusion Welded .112-Inch 2014-T6 Using 716 Filler  
Bead Intact Tested at 600°F Temperature.

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1177 - 1H	16,300	18,600	4.0	6.0	3.5	HAZ
- 2H	16,200	18,600	4.0	6.0	4.5	HAZ
- 3H	15,800	18,500	4.0	6.0	3.5	HAZ
- 4H	16,000	18,400	4.0	6.0	3.5	HAZ
1179 - 5H	16,700	20,400	4.0	6.0	3.5	HAZ
1179 - 6R	15,900	17,200	4.0	6.0	3.5	HAZ
- 7R	---	15,100	4.0	6.0	3.5	HAZ
- 8R	14,200	15,700	4.0	6.0	3.5	HAZ
1180 - 9R	14,700	16,700	4.0	5.0	3.5	HAZ
- 10R	13,400	14,700	4.0	6.0	3.5	HAZ

Table XXIV. Fusion Welded .112-Inch 2014-T6 Using 4043 Filler  
Flush Bead Tested at 600°F Temperature

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1182 - 1HF	13,500	15,600	18.0	9.0	4.5	W
- 2HF	13,700	15,400	12.0	6.0	3.5	W
- 3HF	13,500	15,300	20.0	10.0	5.5	W
- 4HF	13,200	14,900	10.0	5.0	3.0	W
1185 - 5HF	13,000	15,400	18.0	4.0	4.5	W
- 6HF	15,600	16,900	8.0	4.0	2.5	W
- 7HF	12,600	14,300	18.0	9.0	4.5	W
- 8HF	12,500	14,600	18.0	9.0	4.5	W
1186 - 9HF	13,600	15,400	16.0	8.0	4.0	W
- 10HF	12,200	14,000	18.0	9.0	4.5	W

Table XXV. Fusion Welded .112-Inch 2014-T6 Using 716 Filler  
Flush Bead Tested at 600°F Temperature .

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1170 - 1HF	15,200	18,100	8.0	9.0	4.5	HAZ
- 2HF	15,500	18,400	8.0	8.0	4.5	HAZ
- 3HF	15,800	18,900	7.0	6.0	4.5	HAZ
- 4HF	15,100	17,900	7.0	6.0	4.5	HAZ
1169 - 5HF	15,100	18,100	20.0	11.0	5.5	W
1169 - 6RF	13,800	16,100	8.0	9.0	4.5	HAZ
- 7RF	13,500	16,200	8.0	9.0	4.5	HAZ
- 8RF	13,400	16,000	8.0	9.0	4.5	HAZ
1168 - 9RF	14,300	16,900	10.0	10.0	5.0	HAZ
- 10RF	14,200	16,800	14.0	8.0	4.5	HAZ

HAZ - Heat Affected Zone

Table XXVI .112-Inch Clad 2014-T6 Transverse Sheet Strength  
Tested at Room Temperature,

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1167 - 1R	63,000	71,000	---	---	12.0	-
1190 - 2R	64,500	73,000	---	---	9.0	-
1201 - 3R	63,600	71,500	---	---	10.5	-
1200 - 4R	62,500	70,400	---	---	10.5	-
1189 - 5R	65,400	74,700	---	---	11.0	-
1178 - 6R	65,400	73,600	---	---	11.0	-
1188 - 7R	65,000	73,900	---	---	11.5	-
1198 - 8R	61,900	71,000	---	---	11.5	-
1197 - 9R	64,300	72,700	---	---	10.5	-
1199 - 10R	61,900	70,300	---	---	10.5	-

Table XXVII .112-Inch Clad 2014-T6 Transverse Sheet Strength  
Tested at 600° Temperature,

Specimen No.	Yield Stress psi	Ultimate Stress psi	Elongation - %			Type of Failure
			$\frac{1}{2}$ "	1"	2"	
1167 - 1H	17,700	19,800	---	---	10.0	-
1190 - 2H	18,500	20,900	---	---	5.5	-
1201 - 3H	17,500	20,500	---	---	7.5	-
1200 - 4H	17,300	20,100	---	---	4.5	-
1198 - 5H	---	---	---	---	---	-
1187 - 6H	19,300	21,900	---	---	4.0	-
1188 - 7H	---	---	---	---	3.0	-
1189 - 8H	19,900	24,000	---	---	3.0	-
1197 - 9H	17,200	19,200	---	---	3.0	-
1199 - 10H	17,700	19,700	---	---	3.0	-

Table XXVIII. Summary of Tests Performed.

	Quality Panels	Tensiles Transverse	Free Bend Long. Trans	Guided Bend Transverse	Reeves Test	Navy Budge Test	Total tested
<u>Room Temp. Tests</u>							
.063 thk 2014-T6	80	100	12	12	2*	16	234
.112 thk 2014-T6	40	50	12	None	4**	None	118
.190 thk 2014-T6	None	None			8***		8
<u>600°F Temp. Tests</u>							
.063 thk 2014-T6		100					100
.112 thk 2014-T6		50					50
<u>-65°F Temp. Tests</u>							
.063 thk 2014-T6						4	4
<u>+160°F Temp. Test</u>							
.063 thk 2014-T6						4	
Totals	120	300	24	12	14	24	
				GRAND TOTAL			518

\* One each, 4043, 716  
 \*\* Three 4043, one 716  
 \*\*\* Six 4043, two 716



Table XXIX. Longitudinal Free-Bend Specimen Test Results .063-Inch  
Thick 2014-T6 Alclad Aluminum Sheet Material.

Specimen No.	Filler Material	Condition of Bead	Type Specimen	Free-bend Angle, degrees	Location of Failure
1	716	Intact	Face	170	Transverse Crack across face of bead
2	716	Intact	Face	165	Transverse Crack across face of bead
3	716	Intact	Face	160	Transverse Crack across face of bead
11	716	Flush	Face	175	Transverse Crack across face of bead
22	716	Flush	Face	180	Transverse Crack across face of bead
33	716	Flush	Face	180	Transverse Crack across face of bead
1	4043	Intact	Face	180	Transverse Crack across face of bead
2	4043	Intact	Face	180	Transverse Crack across face of bead
3	4043	Intact	Face	180	None
11	4043	Flush	Face	180	None
22	4043	Flush	Face	180	None
33	4043	Flush	Face	180	50% transverse crack across face of bead

Table XXX. Longitudinal Free-Bend Specimen Test Results .112-Inch  
Thick 2014-T6 Alclad Aluminum Sheet Material.

Specimen No.	Filler Material	Condition of bead	Type specimen	Free-bend Angle, degrees	Location of Failure
1198-1	716	Intact	Face	45	Transverse crack across face of weld
1199-2	716	Intact	Face	42	Transverse crack across face of weld
1197-3	716	Intact	Face	40	Transverse crack across face of weld
1198-1	716	Flush	Face	75	Transverse crack across face of weld
1199-2	716	Flush	Face	78	Transverse crack across face of weld
1197-3	716	Flush	Face	80	Transverse crack across face of weld
1205-1	4043	Intact	Face	106	Transverse crack across face of weld
1206-2	4043	Intact	Face	105	Transverse crack across face of weld
1204-3	4043	Intact	Face	115	Transverse crack across face of weld
1206-1	4043	Flush	Face	128	Transverse crack across face of weld
1205-2	4043	Flush	Face	120	Transverse crack across face of weld
1204-3	4043	Flush	Face	130	Transverse crack across face of weld

Table XXXI. Transverse Free-Bend Specimen Test Results .063-Inch  
Thick 2014-T6 Alclad Aluminum Sheet Material.

Specimen No.	Filler Material	Condition of bead	Type Specimen	Free-Bend Angle, degrees	Location of Failure
1	716	Intact	Face	145	Heat-affected zone
2	716	Intact	Face	160	Heat-affected zone
3	716	Intact	Face	150	Heat-affected zone
11	716	Flush	Face	67	Fusion line
22	716	Flush	Face	65	Fusion line
33	716	Flush	Face	70	Fusion line
1	4043	Intact	Face	160	Heat-affected zone
2	4043	Intact	Face	153	Heat-affected zone
3	4043	Intact	Face	145	Heat-affected zone
11	4043	Flush	Face	70	Fusion line
22	4043	Flush	Face	67	Fusion line
33	4043	Flush	Face	65	Fusion line

Table XXXII. Transverse Free-Bend Specimen Test Results .112-Inch Thick 2014-T6 Alclad Aluminum Sheet Material.

Specimen No.	Filler Material	Condition of Bead	Type Specimen	Free-Bend		Location of Failures
				Angle	degrees	
1190-1	716	Intact	Face	50		Fusion line
1190-2	716	Intact	Face	58		Fusion line
1190-3	716	Intact	Face	60		Fusion line
1190-1	716	Flush	Face	40		Weld metal
1190-2	716	Flush	Face	35		Weld metal
1190-3	716	Flush	Face	35		Weld metal
1196-1	4043	Intact	Face	70		Fusion line
1196-2	4043	Intact	Face	60		Fusion line
1196-3	4043	Intact	Face	90		HAZ-Base metal
1196-1	4043	Flush	Face	45		Weld metal
1196-2	4043	Flush	Face	48		Weld metal
1196-3	4043	Flush	Face	55		Weld metal

Table XXXIII. Transverse Guided-Bend Specimen Test Results .063-Inch Thick 2014-T6 Alclad Aluminum Sheet Material.

Specimen No.	Filler Material	Condition of Bead	Type Specimen	Bend Angle degrees	Location of Failure
1	716	Intact	Face	95	Fusion line
2	716	Intact	Face	98	Fusion line
3	716	Intact	Face	100	Fusion line
11	716	Flush	Face	45	Weld Metal
22	716	Flush	Face	42	Weld Metal
33	716	Flush	Face	40	Weld Metal
1	4043	Intact	Face	70	Weld Metal
2	4043	Intact	Face	65	Weld Metal
3	4043	Intact	Face	80	Weld Metal
11	4043	Flush	Face	60	Weld Metal
22	4043	Flush	Face	65	Weld Metal
33	4043	Flush	Face	70	Weld Metal

Tensile tests summaries show a definite superiority in yield strength of 716 filler wire for room-temperature properties. This superiority is more evident when the bead reinforcement is removed, for both .063-inch and .112-inch material, and amounts to about 7 to 9 percent in joint efficiency. At 600°F this apparently superior yield strength of 716 is the same. The ultimate strength of both materials, however, is about the same.

It was noted in the heat-affected zone of the parent material that 12 of 20 716 .063-inch flush bead specimens were tested at 600°F, and all but one of the .112-inch specimens failed. All the 4043 specimens failed in the weld. This shows a definite superiority of the 716 over the 4043 filler material. All the 4043 and 716 test specimens, flush bead, tested at room temperature failed in the weld metal. All 4043, .064 and .112-inch bead intact specimens, tested at room temperature, failed in the fusion-zone area. The 716, .063-inch bead intact, tested at room-temperature, failed in the weld-metal. The 716, .112-inch specimen bead intact, tested at room temperature, failed fusion-and-heat-affected zone areas. All 4043 specimens, bead intact, tested at 600°F failed in the heat-affected zone. All 716 specimens, bead intact, tested at 600°F, failed in the heat-affected zone.

#### Bend Tests

To obtain a better indication of the ductility of the 716 and 4043 filler metals, the longitudinal free-bend test specimen simulating a circumferential weldment, was used. Transverse free-bend specimens were tested to determine the ductility of the weld-joint. The transverse guided-bend test specimens were also tested to determine the basic soundness of the weld joint. Test specimens were used with the weld reinforcement intact, and with the weld bead flush.

#### Longitudinal Free-bend Tests

The longitudinal free-bend test was used to determine the ductility of the two filler metals. These bend tests indicated that regardless of the two sheet thicknesses welded (0.063 and 0.112-inch sheet materials), the 4043 weld-metal had the better ductility. The cracks that occurred were transverse across the face of the weld bead. These results were expected since the 716 weld metal is of the precipitation-hardening type.

#### Transverse Free-bend Test

To determine the ductility of the heat-affected zone of the 2014-T6 base metal, the transverse free-bend specimen was used. These test results showed that, with the 0.063-inch material with weld reinforcement intact, the failure occurred in the heat-affected zone with a bend angle that varied between 145° to 160° for both filler materials indicating comparable ductility. When the weld reinforcement was flush with the base metal, failure occurred along the weld-fusion line with a bend angle that varied between 65-70°. These results indicated that the fusion line is the weakest zone of the weld area for this material. This zone is normally the weakest because of the large grain growth that occurs during the welding operation.

The 0.112-inch transverse free-bend specimens, with the 716 weld reinforcement intact, were bent through a 50-60° angle and failed in the fusion line area in all three specimens tested. The 4043 weld metal, 0.112-inch specimens (weld reinforcement intact), underwent a 60-90° bend angle. Failure for two of the specimens occurred in the fusion line area. The third specimen, which had a 90 degree bend angle, broke in the heat-affected zone and parent metal. These results show that the 4043 specimens had slightly better heat-affected zone ductility. Failure generally occurred in the fusion line area which is the weakest because of the large grain growth that occurs during welding.

The 0.112-inch flush specimens had bend angles of 35-40° for the 716 filler material and 45-55° for the 4043 metal. The 4043 specimens had the greater ductility. Failure occurred in the weld metal for both filler materials tested. These results indicate that, when the weld reinforcement is removed, the fusion line and heat-affected zone areas are not the weakest, but the weld metal itself becomes weak. When the reinforcement is removed the center of the weld metal is usually the weak region because of the dendritic junction that results from the final solidification at the center of the weld.

#### Transverse Guided-bend Test

The transverse guided-bend test was used to check the soundness of the 0.063-inch weldments. This test was also used to determine the action of the weld metal and the heat-affected zones on the ductility of the weld joint due to the additional restraint imposed by the bend jig. Some interesting results were obtained. As might have been expected, the transverse guided-bend test was more severe than the transverse free-bend test. In all the conditions, except the 4043 flush, the degree of specimen bending was less for the guided-bend specimens. The one 4043 flush specimen broke at 65° instead of 60° when the free-bend was used. Thus the results for this group could be considered the same. The important result of the guided-bend test is that the location of failure was changed in three instances from the heat-affected, or fusion line, areas to a failure in the weld metal. It should be noted that by using the guided-bend test, the 716 bead-intact specimen failed in the fusion line. The free-bend specimens failed in the heat-affected zone. The fusion line is the least ductile joint area. The 4043 bead-intact guided-bend test specimens failed in the weld metal and not in the fusion line as did the 716 specimens. These results showed that the 4043 filler metal is the weaker of the two when placed under severe deformation.

In both the 716 and 4043 flush guided-bend specimens, failure occurred in the weld metal due to the severe restraint and reduced area cross-section. The free-bend flush specimens for both filler materials failed in the fusion line area indicating lower ductility and/or strength.

#### Corrosion Test

The results of the 288-hour salt spray atmosphere tests indicated that no appreciable corrosion was observed in either of the filler materials or the heat-affected zones of the two weldment types when compared to unwelded base metal sheets. The depth of penetration of the 4043 weldment heat-affected zone was double that of the 716 weldment. However, in no case did either corrosion

penetration exceed more than one-half the thickness of the cladding material (0.003-inch thick). In all instances of corrosion, the path was transgranular in nature.

No tensile specimens were exposed and tested in salt spray atmosphere. Previous investigations have shown that tensile and yield strength was decreased 5 and 16 percent respectively on .051-inch 2014-T6 aluminum sheet welded manually with 4043 filler material and tested in the as-welded condition for a similar 288-hour exposure (Reference 11). The corrosion tests were performed because the missile might be exposed to salt atmosphere.

The effect on the weld metal and heat-affected zones was determined by metallographic examination. After corrosion testing, unwelded, .063-inch 2014-T6 control panels and welded panels were removed from the salt-spray chamber, sectioned, and metallographically examined. The following results were obtained:

- (a) Both weld filler materials (716 and 4043) showed a maximum penetration depth of .0004 inch.
- (b) The penetration into the cladding material of the sheet in the heat-affected zone near the weld bead was .00063-inch in the 716 weldment and .00125-inch in the 4043 weldment.
- (c) No corrosion was observed which penetrated more than one-half the thickness of the cladding material (.003-inch thick) in the heat-affected zones.
- (d) In all the above corrosion instances the type of penetration was transgranular in nature.
- (e) Unwelded sheet showed .0017-inch penetration.

#### Hardness Surveys

The results of the hardness surveys indicated that the 716 weld metal was harder (Rockwell "B" 41), due to precipitation-hardening, than the 4043 filler material (Rockwell "B" 28). The hardness of the 716 weld metal accounts for the increase in strength of this filler material as compared with the 4043 metal. It should also be noted, from Figure 13, that the 716 weld metal has a greater variation in hardness. This variation could probably be caused by the micro-segregation resulting from the mixing of the 2014-T6 copper-bearing aluminum alloy sheet and the copper-bearing aluminum filler material, 716 alloy. A microphotograph of this segregation can be seen in Figure 14, and enlarged in Figure 15. Figures 16 and 17 are macrographs of the hardness survey.

As can be seen in the hardness transverse plot, Figure 13, the heat-affected zone of the 716 weldment has experienced more annealing than the 4043 weldment. Special notice should be taken of the area immediately adjacent to the fusion line in the 716 weldment hardness transverse. A reading of Rockwell "B" 31 was experienced as compared with no such drop in hardness of the 4043 weldment. Another drop in hardness to Rockwell "B" 45 from 52 was experienced in the 716



weldment at a distance of .200 to .240 inch from the center of the weld. These noticeable changes in hardness, due to the annealing that takes place in the heat-affected zone are caused by the welding heat. This annealing could probably be caused by the fact that more of the energy input (the same in both weldments) is dissipated into the heat-affected zone since the 716 filler material has a 100°F lower melting temperature and required less heat to melt than the 4043 filler material. This theory would require additional investigation.

### Metallographic Results

The effects of the welding process and filler material on the mechanical properties is of considerable interest to the Pershing welding component program at Martin-Orlando. The microstructures of the two weld metals under investigation are specifically affected. The effects of the heat-affected zones on the microstructure are secondary.

Because of the very high rates of solidification (much greater than experienced in any casting process), deposits exhibit very fine dendrite textures leading to unique mechanical properties and rapid response to heat-treatment, if required after the welding operation. This fine microstructure of the inert-arc weld deposit is shown in Figures 14 and 15 for the 716 weld metal and Figures 18 and 19 for the 4043 weld metal. As can be seen from these microphotographs, the dendrites in the weld metal are very fine and do not have the typical tree-like structures so often observed in castings.

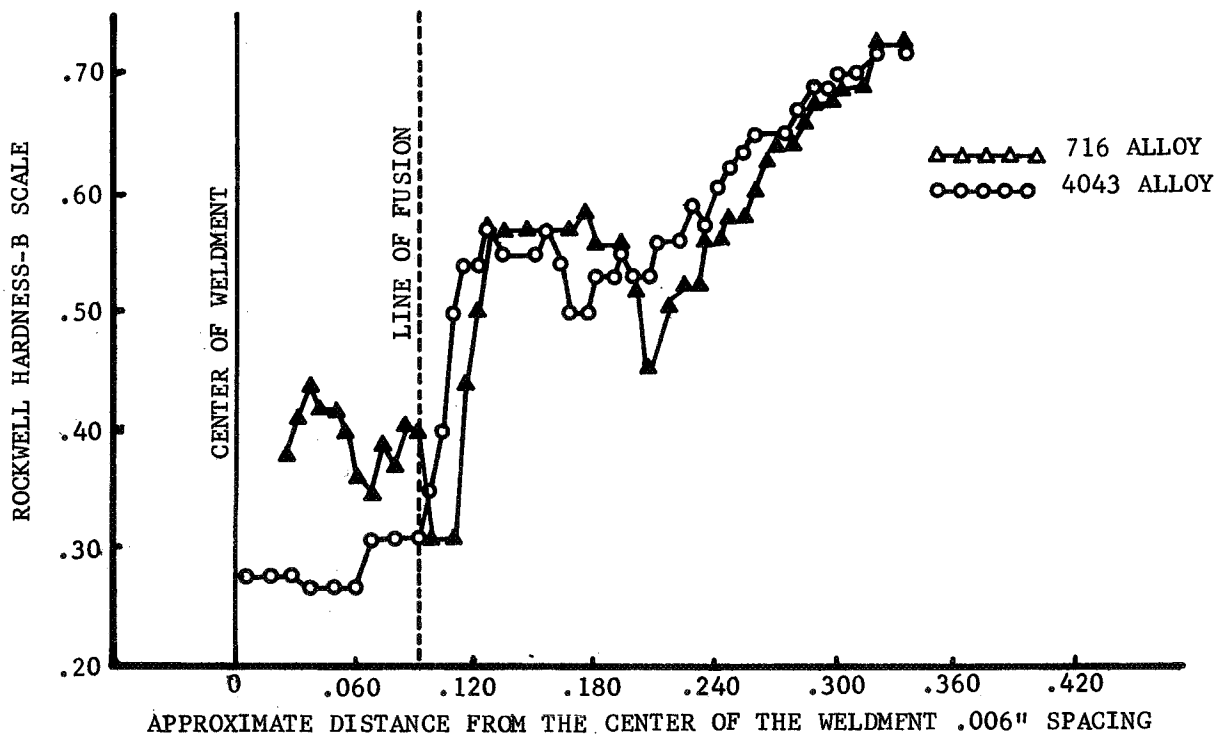
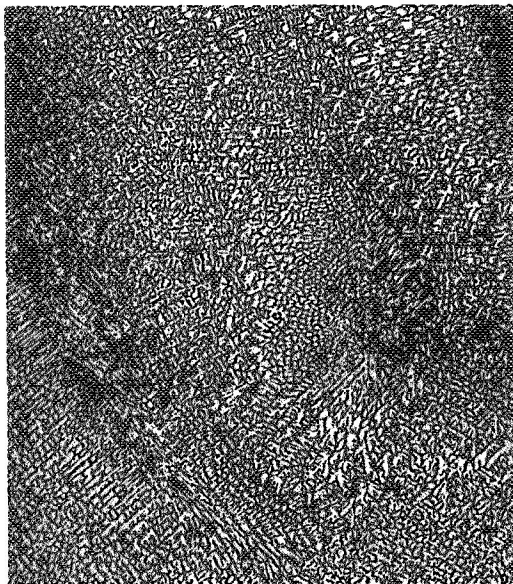
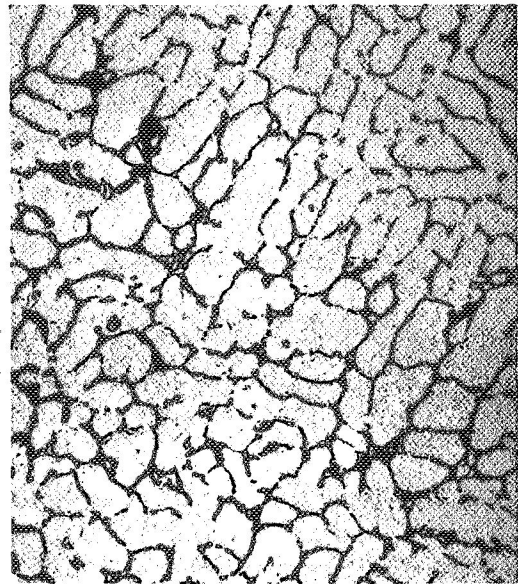


Figure 13. Hardness Survey on 0.063-inch 2014-T6 Aluminum Alloy Sheet

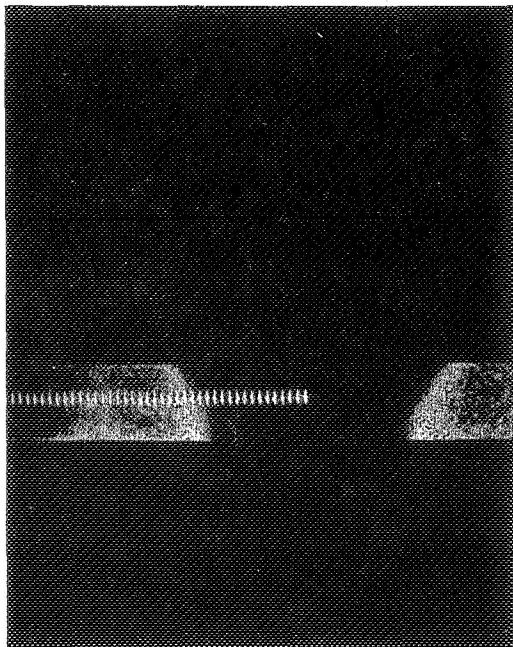


Neg. #0574 (100x)  
Figure 14. 716 Weld Metal

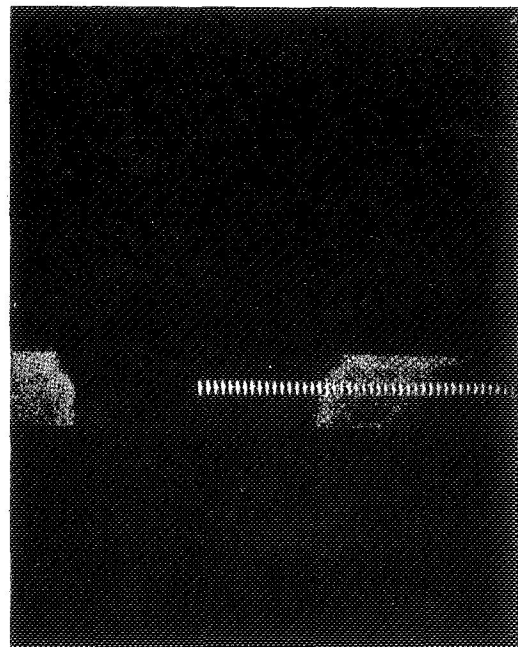


Neg. #0651 (500x)  
Figure 15. Enlargement of 716 Weld Metal

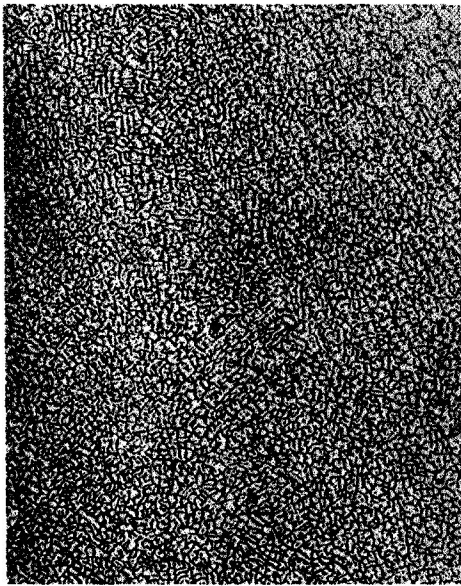
Transverse to Arc Travel and Perpendicular to the Plate Surface Energy Input of 5,700 joules/inch



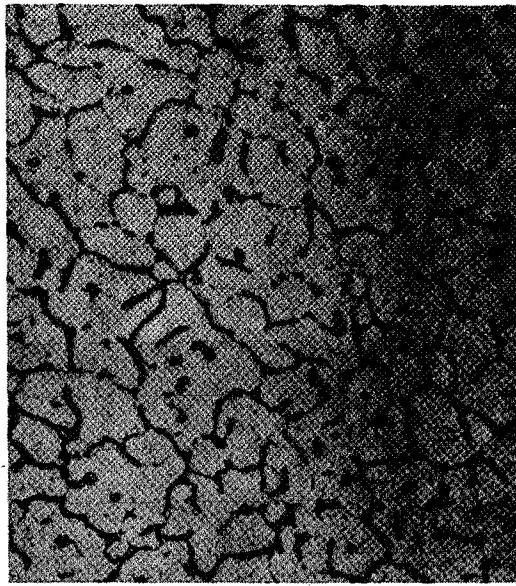
Neg. #0574 (5x)  
Figure 16. Hardness Survey of 716 Weldment - 0.063-inch. Keller's Etchant.



Neg. #0574 (5x)  
Figure 17. Hardness Survey of 4043 Weldment 0.063-inch Thick. Keller's Etchant



Neg. #0574 (100x)  
Figure 18. 4043 Weld Metal



Neg. #0551 (500x)  
Figure 19. Enlargement of 4043  
Weld Metal

Transverse to Arc Travel and Perpendicular to the Plate Surface Energy Input  
of 5 700 joules/inch.

The fine structure observed is due to the rapid solidification of the weld deposit. This does not permit time for the nucleated grain to grow as it would in a casting. The high rate of solidification permits very little liquid metal to form and very little diffusion to take place. Thus, in effect, the dendritic mechanism of solidification is the means by which nature solves the mass transport problem which results in the liquid when aluminum-rich crystals precipitate from an aluminum-copper melt similar to the inert-arc weld deposit (Reference 12).

The interdendritic spacing, which can be observed metallographically, is an important structural characteristic of many cast alloys. It is a measure of the dimensions of the liquid zones which were prevalent during solidification. Since the mass-transport theory governs this characteristic dimension and it is time dependent, it should be expected that the more rapid solidification, the finer the dendritic structure (Reference 12).

The energy input used in this investigation was the same for both filler metals; hence the structures were about equal. If different energy inputs were used, differences in the size of the weld metal dendrites would be noted. In Figure 14, microsegregation can be observed in the 716 weld metal. This phenomenon was possible because the filler material in question was an aluminum-copper alloy which is more prone to partial "unmixing" brought about by the freezing of the molten weld deposit. This microsegregation is caused by the fact that, when a solution starts to solidify, the composition of the first solid which forms is substantially different from that of the liquid.

The detailed pattern in which the solute (copper) distributes itself relates to the dendritic character of solidification which, in turn, results from the limited rate with which solute (copper) can diffuse through the liquid during freezing. It can be observed that there is no microsegregation present in the 4043 weld metal structure (Figure 18). To eliminate the microsegregation present in the 716 weld metal, a suitable heat-treatment would be required to permit diffusion to take place and result in a homogeneous structure.

The fusion line microstructure for the 716 and 4043 weldments is shown in Figures 20 and 22 respectively. Here it can be seen that tree-like dendrites did form since solidification started here first and there was time for diffusion to take place. The center of the weld metal freezes last and very rapidly, and results in the fine structure. These microphotographs show that the 716 fusion line has a coarser dendrite structure than the 4043 structure with a more pronounced segregation. These factors can be the contributing items, to the greater ductility of the 4043 transverse bend specimens. Additional discussion of the factors affecting the bend ductility will follow later.

As indicated by the hardness transverses and microphotographs (Figures 20, and 22), the heat-affected zone in the 716 weldment had a larger amount of annealing than the 4043 weldments. Since the energy input was the same (5,700 joules/inch for both filler materials), the apparent difference in heat input observed in the heat-affected zone may have been due to the difference in heat-absorption while the two filler materials were melted.

The 4043 filler material has a liquidous temperature, about 100°F higher than the 716 metal. Additional experimental work would be required to prove this hypothesis.

A microphotograph of a typical cross-section of a transverse-bend specimen which fractured in the heat-affected zone is shown in Figure 23. Here failure was due primarily to the continuous intermetallic grain-boundary precipitate ( $\text{Cu Al}_2$ ) caused by the heat of welding. This instance is typical in the majority of like projects. Other intermetallic compounds which may form at the grain-boundary and have added to the brittleness include the  $\text{Al-Cu-Fe-Si}$  constituent and  $\text{Cu Mg}_5 \text{Si}_4 \text{Al}_4$  (Reference 13). This brittle grain-boundary network of intermetallics, bordering the fracture and completely encompassing the adjacent grains, is very evident. The inert-arc welding process has caused the sheet material in the heat-affected zone to be rapidly heated to a very high temperature for a short time and then cooled to room temperature. The material does not remain at the high temperature long enough to result in incipient melting of the ternary and quaternary eutectics. However, during the cooling



Neg. #0574 (100x)

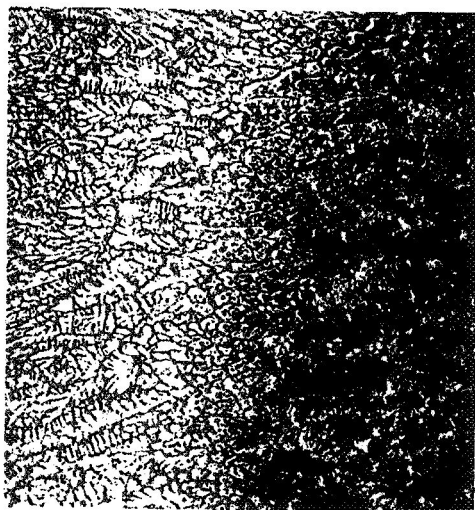
Figure 20. 716 Weld to Base Metal Transition Zone

Transverse to Arc Travel and Perpendicular to the Sheet Surface.



Neg. #0574 (100x)

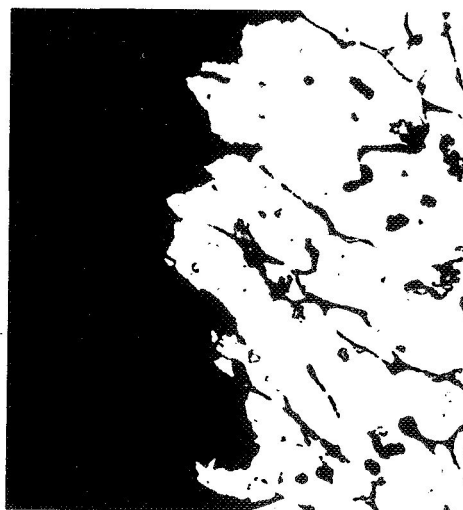
Figure 21. 2014-T6 Base Metal



Neg. #0574 (100x)

Figure 22. 4043 Weld to Base Metal Transition Zone

Transverse and Perpendicular to Arc Travel. Keller's Etchant



Neg. #0656 (1500x)

Figure 23. Cross-section of bend failure through H. A. Z.

process large quantities of copper alumunide ( $\text{CuAl}_2$ ) and other intermetallics are precipitated. The quantity precipitated in a grain boundary is a function of the grain surface-to-mass ratio at that point. Resolution, or agglomeration, may be affected by heat-treatment if maximum ductility and toughness are required in the production weldment. (The fact that the 716 weld metal is strong, and possesses more ductility in the weld metal than the heat-affected zone, may be due to the very fine dendrites plus a fine dispersion of intermetallic compounds established by the rapid solidification rate after welding.) Since the Pershing weldments are used in the as-welded condition some of the ductility loss in the transverse bend specimens may be caused by this grain-boundary precipitate. Serious loss of ductility is precluded by the simultaneous formation of a soft and ductile matrix which is not present in the solution-treated and artificially-aged weldments (Reference 13).

The occurrence of intergranular precipitants in the heat-affected zone (copper-bearing aluminum alloys) lowers the corrosion resistance of unclad material. This applies to a lesser degree, in clad materials if and when protective cladding is removed by corrosive chemical cleaning solutions. Therefore, care must be taken to limit the time of exposure and to prevent the use of these corrosive solutions. Only by these precautions, can intergranular corrosion be controlled.

The microstructure study of the .112-inch sheet weldments was similar to the .063-inch sheet weldment results.

#### The Reeves Restrained Crack-sensitivity Test Results

The Reeves restrained crack-sensitivity sheet specimen test did not produce cracking in either the 716 or the 4043 filler material when normal air cooling was used. (See Figure 24.) However, one .112-inch thick 4043 restraint specimen did crack in the weld when air blast was used. Another 4043 specimen, .190-inch thick, also cracked but this occurred in the 4043 fillet weld that restrained the sheet specimens (Table XXXIV). The fillet weld filler material was changed to 716 filler metal and the restraint test duplicated, using the 4043 material for the test weld and air-blast cooling. No cracking resulted. One possible cause for the few cracks is the fact that extra-heavy duty "C" clamps were not available to hold the sheet specimen to the restraining plate during the fillet welding operation. This lack of pin-pointed restraint permitted the sheet specimens to open up the root gap to .035-inch. This opening did not permit the original tight butt-joint which would have produced some of the residual stresses which help induce cracking. However, the 4043 weld metal did crack under the restraint present for two of the test specimens. The writer had used the same test to produce cracks in Inconel with excellent results. Other investigators have also used this restraint test to successfully check filler material crack susceptibility.

#### Navel Research Laboratory Sheet Bulge Test Results

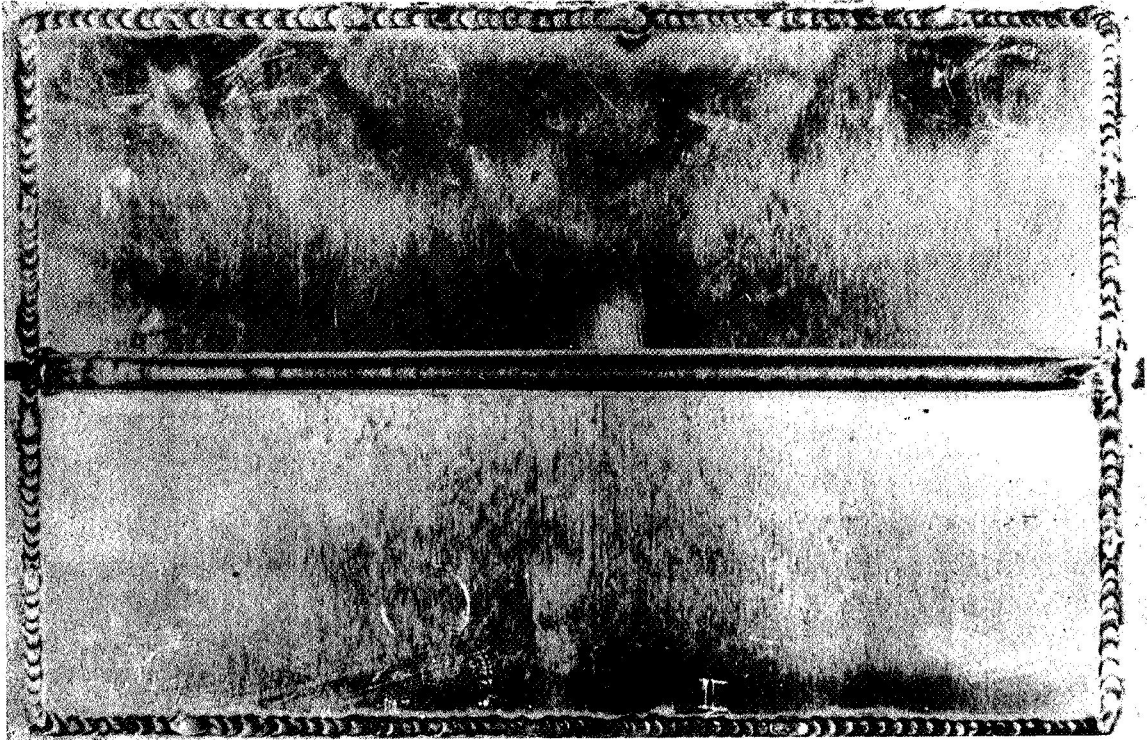
From the start of the weld-filler-material-evaluation program, the 2014 weldments were known to lack ductility. However, the minimum ductility required in a pressure-vessel weldment was not known. To help answer this question, the simple and inexpensive N.R.L. sheet bulge test was used to evaluate weldments under simulated operating conditions, and also to act as a small

Table XXXIV. Reeves Restrained Crack-sensitivity Sheet Specimen Test Results  
0.063-, 0.112, and 0.190-Inch Thick 2014-T6 Alclad Aluminum Sheet Material.

Test No.	Joint Design	Root Gap, Inches	Material Thickness Inches	Filler Material, type	Method of		Cracking Results	Remarks
					Cooling	After Welding		
1	Square- groove Butt	0.035	0.063	716	Normal Air		None	None
2	Square- groove Butt	0.035	0.063	4043	Normal Air		None	None
3	80° In- cluded Angle, 1/32- inch land	0.035	0.112	716	Normal Air		None	None
4	"	0.035	0.112	4043	Normal Air		None	None
5	"	0.035	0.112	4043	Air Blast		None	3" Long Crack in Weld Metal, at End of Weld-Maximum Restraint
6	"	0.035	0.112	4043	Air Blast		None	None
7	"	0.035	0.190	4043	Normal Air		None	None
8	"	0.035	0.190	4043	Normal Air		None	None
9	"	0.035	0.190	4043	Normal Air		None	None
10	"	0.035	0.190	716	Normal Air		None	None
11	"	0.035	0.190	4043	Air Blast		None	None
12	"	0.035	0.190	4043	Air Blast		Yes	12" crack in 4043 fillet weld
13	"	0.035	0.190	4043	Air Blast		None	Fillet Weld Changed to 716
14	"	0.035	0.190	716	Air Blast		None	Fillet Weld Changed to 716



Figure 24. Typical Reeves Restrained Sheet Crack-sensitivity Test Specimen



Neg. #0617

(50% Reduction)

pressure-vessel test in itself. The bulge test was used for comparison (Table XXXV). Since time was a factor, this test was given only limited application for weld-zone performance to determine any potential weak weldment areas.

The test results in Table XXXV, show no failures in any of the specimens tested with the weld bead intact at room temperature (+78°F), elevated-temperature (+160°F), or sub-zero temperature (-65°F). The three ranges simulated typical operating conditions for missiles of this type. The bulge heights in all the specimens with the weld reinforcement intact were measured, and it was found that the root specimens (the root fibers having the maximum strain) had the largest deflection. The reason for this greater bulge was the root weld reinforcement which is less than the face reinforcement of the weldment and therefore, not as strong.

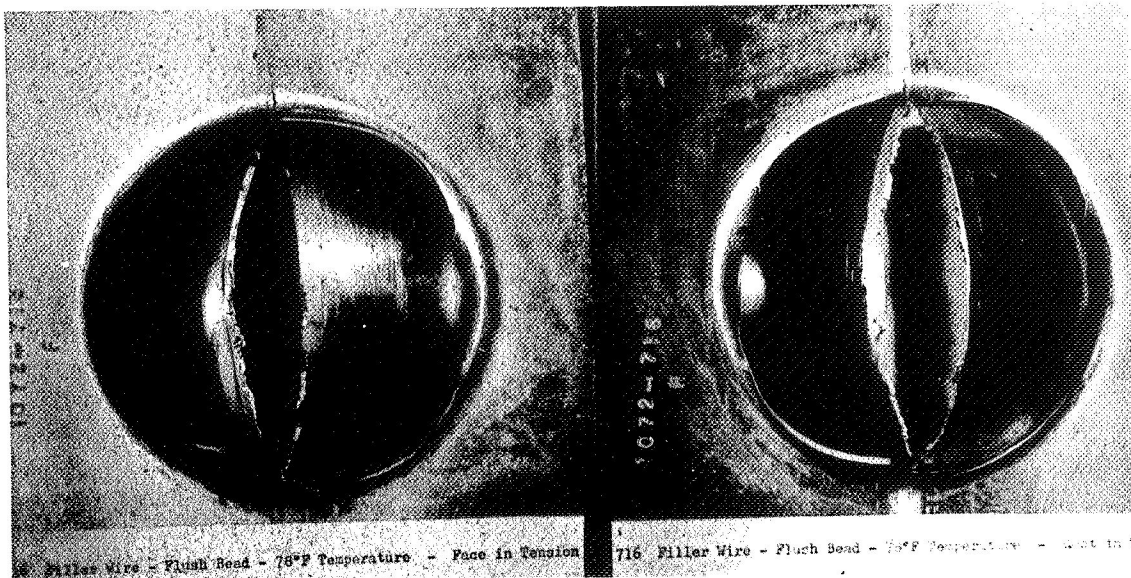
When the weld reinforcement was removed flush with the base metal, from both the face and root of the weldment, failure was obtained. This occurred when the test was conducted at room temperature (78°F). The test specimens, welded with the 716 filler material, failed with low ductility in the heat-affected and fusion line areas as shown in Figure 25. The 4043 test specimens failed in the center of the weld metal (Figure 26). Although a limited number of tests were made in this series, it became evident that the 716 filler material was the stronger of the two test metals.

To take advantage of the sheet bulge test for the weld-zone performance test, a bulge height must be determined that corresponds before the yield point is reached, using a 0.2 percent offset by obtaining strain-gage readings. Additional work must be done with various dies. The tests conducted in this



Table XXXV. Naval Research Laboratory Sheet Bulge Specimen Test Results  
0.063-Inch Thick 2041-T6 Alclad Aluminum Sheet Material.

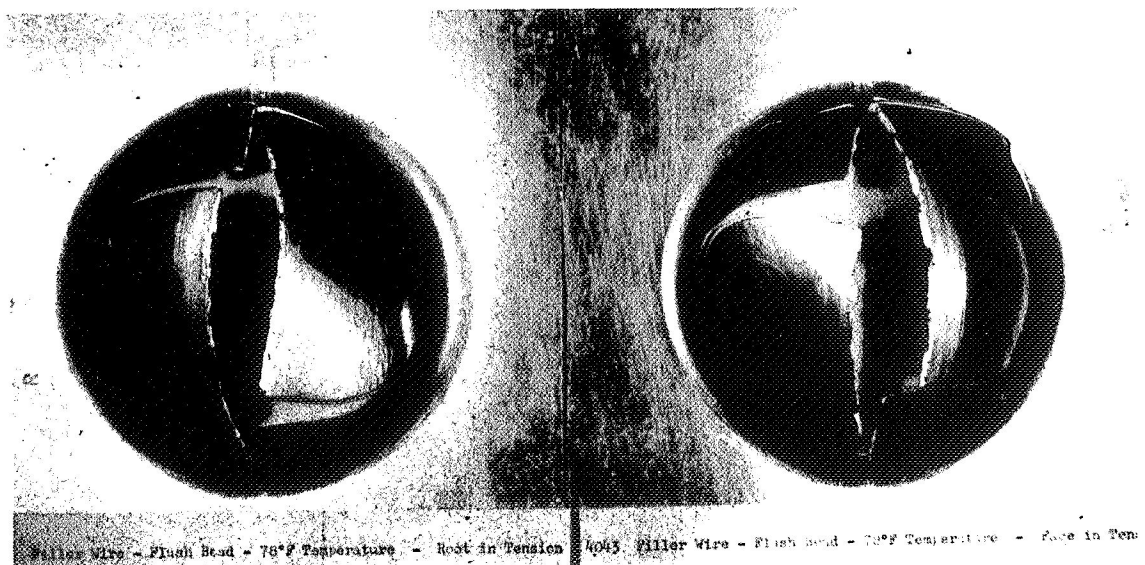
Panel Number	Filler Material	Type of Specimen	Specimen Location in Panel	Testing Temperature, °F	Bead Reinforcement	Die Type	Bulge Deflection	Result
980	716	Root	Start	+78	Intact	Open	0.307	No Failure
989	716	Root	Start	+78	Intact	Open	0.291	No Failure
990	716	Root	Start	+78	Intact	Open	0.313	No Failure
991	716	Root	Start	+78	Intact	Open	0.290	No Failure
1068	716	Face	Center	+78	Intact	Open	0.237	No Failure
1068	716	Root	Start	+78	Intact	Open	0.295	No Failure
1033	4043	Root	Start	+78	Intact	Open	0.274	No Failure
1034	4043	Root	Start	+78	Intact	Open	0.258	No Failure
1090	4043	Root	Start	+78	Intact	Open	0.282	No Failure
1091	4043	Root	Start	+78	Intact	Open	0.258	No Failure
1027	4043	Face	Center	+78	Intact	Open	0.250	No Failure
1027	4043	Root	Start	+78	Intact	Open	0.260	No Failure
1064	716	Face	Center	+160	Intact	Open	0.248	No Failure
1064	716	Root	Start	+160	Intact	Open	0.255	No Failure
1030	4043	Face	Center	+160	Intact	Open	0.265	No Failure
1030	4043	Root	Start	+160	Intact	Open	0.276	No Failure
1066	716	Face	Center	-65	Intact	Open	0.232	No Failure
1066	716	Root	Start	-65	Intact	Open	0.266	No Failure
1035	4043	Face	Center	-65	Intact	Open	0.241	No Failure
1035	4043	Root	Start	-65	Intact	Open	0.248	No Failure
1072	716	Face	Center	+78	Flush	Open	1.274	HAZ-Fusion Line-Weld metal
1072	716	Root	Start	+78	Flush	Open	1.224	HAZ-Fusion Line
1036	4043	Face	Center	+78	Flush	Open	1.374	Center of Weld Metal
1036	4043	Root	Start	+78	Flush	Open	1.398	Center of Weld Metal



Neg. #0600

(50% Reduction)

Figure 25. Navy Bulge Test Specimens Welded With 716 Filler Metal, Flush-bead.



Neg. #0600

(50% Reduction)

Figure 26. Navy Bulge Test Specimens Welded With 4043 Filler Metal, Flush-bead.

series used the open-die, the maximum 300-lb test load, the maximum drop-height of eight feet causing forced fractures. To establish weldment fracture performance under known conditions of elastic or plastic strains, it is necessary to limit the allowable bulge deformation with the help of interchangeable, solid die-cups for increasing bulge depths. By investigating these test conditions, information will be provided to determine the origin of failure, the level of prefracture deformation at which failure initiates, the presence, or absence, of preferential paths of failure, and the extent and type of resulting failure.

The sheet and filler materials used in this investigation were within the required applicable specification limits for the particular material in question.

All the tests conducted in this investigation indicate that the 716 filler material is the stronger of the two. The 4043 filler material, in the majority of cases, had the greater ductility. When applied to the Pershing missile, the 716 filler material should continue to be used with confidence as specified in the Army Ballistic Missile Agency specification ABMA-PD-W-45A.

#### Acknowledgement

The author wishes to acknowledge the assistance provided by Messrs. Rudy Spanholtz and Alan R. Mortensen of the Materials Engineering Department for pulling and evaluating all the tensile specimens respectively, to Mr. John Berndobler of Advanced Manufacturing Technology for performing all the weld test and preparation of the specimens, to Mr. C. Minnich of Quality Control for performing the many radiographs required, and to Vladimir Mandl who edited and coordinated the publication of this report.

#### SUMMARY OF TEST RESULTS\*

This report describes a laboratory investigation of two weld metals and welded joints using the filler materials in alclad 2014-T6 sheet. These studies were made under controlled conditions in an effort to duplicate and ultimately find the best suited filler metal for Pershing component weldments. The results of this investigation may be summarized as follows:

1. The study of weldments made with high-purity shaved 716 and commercial high-quality vacuum packed shaved 4043 filler materials indicate that both are basically equal as far as cleanliness is concerned. 4043 is somewhat cleaner. Both wires met ABMA-R-27A radiographic requirements, as specified for the Pershing missile.

2. From a mechanical property standpoint, the use of 716 filler material in fusion butt-welded transverse tensile specimens, produced a weld of significantly higher yield strength (4 to 9 percent) when compared to the 4043 material. This is true at both room and elevated temperatures (78 and 600°F respectively).

\* All percentages are in reference to base metal which was pulled at same temperature.

In the critical temperature zone of 600°F, the .063-inch intact ultimate and yield strength results of specimens welded with 4043 are essentially equal to those welded with 716. Removal of the weld reinforcement had no effect on the 716 specimens, but reduced the weld yield and tensile strengths of the 4043 specimens by 7 and 9 percent.

Room temperature .064-inch intact ultimate tensile strengths are essentially equal. Yield strength of 4043 specimens is 4 percent weaker than comparable 716 specimens. Removal of weld reinforcement lowered 716 ultimate and yield by 15 and 7 percent respectively; and 4043 specimens, 21 and 12 percent respectively. In all instances, the strengths of the weld joints were more than adequate for Pershing application.

Corresponding ultimate and yield strengths of all .112-inch thick 716 and 4043 specimens, pulled at room temperature, and 600°F, are within 0-12 percent of each other with the 600°F specimens being within 0-2 percent.

3. Location of failure of the bead-intact 4043 tensile specimens was in the fusion area at room temperature in both the .063 and .112-inch thicknesses. At 600°F, failure occurred in the heat-affected zone.

All intact .063 and .112-inch 716 specimens, except for .063-inch room temperature specimens, failed in the heat-affected zone at room temperature and 600°F. The .063-inch room temperature specimens failed in the weld near the fusion zone.

Flush-bead specimens of both 716 and 4043 failed in the weld metal at room temperature. At 600°F, the 4043 specimens continued to fail in the weld while the majority of the 716 specimens failed in the heat-affected zone.

4. The longitudinal 4043 free-bend tests demonstrated the better ductility of the two filler metals tested. These results included bead-intact and flush-bead specimens bent at room temperature. The transverse .063-inch free-bend specimens, bead-intact and flush-bead, welded with both filler materials, failed in the same heat-affected and fusion areas. The bend angles to initial failure and low ductility-type fracture were the same for both filler materials.

The transverse 0.112-inch free-bend specimens, bead-intact and flush-bead, welded with both filler materials, failed in the same fusion and center of the weld metal zones. The characteristic low-ductility-type failure occurred for both filler materials, although the 4043 specimens had the greater ductility. The transverse 0.063-inch guided-bend specimens, bead-intact, welded with 716 filler material, failed in the fusion zone and had the greater ductility than the bead-intact 4043 specimens which failed in the weld metal. The flush-bead specimens, welded with both filler materials, failed in the weld metal. The 4043 specimens had the greater ductility. All failures were low-ductility-type in nature. No 0.112-inch transverse guided-bend specimens were made. Therefore, no results are reported.

5. Salt spray atmosphere chamber tests, after 288 hours of exposure, indicate that corrosion penetrates a maximum of one-half the thickness of the cladding material in unwelded and heat-affected weldment zones. No appreciable corrosion was apparent in either of the materials investigated.

6. Hardness transverse tests indicate that the 716 filler material is harder than its 4043 counter part because of precipitation hardening. The 716 weld metal has greater variations in hardness than 4043 weld metal, and 716 produced more pronounced annealing of the fusion and heat-affected zones.

7. Metallographic examination revealed the following:

(a) brittle grain-boundary intermetallic compounds are responsible for the reduced ductility of the heat-affected zone of 2014 aluminum-alloy sheet weldments.

(b) the high solidification rates of inert-arc welds result in a very fine microstructure which contributes to the strength of the weld metal.

(c) the 716 weld metal was more susceptible to microsegregation than the 4043 weld metal.

(d) the arc-energy input, used in the welding process, determined the weld metal solidification rate, and subsequent degree of fineness of the weld metal, fusion, and heat-affected weldment zones.

8. Weld metal cracking did not occur in either filler material when normal air cooling was used. However, some cracking was produced in the 4043 specimens when air blast cooling was used. No cracking was produced in 716 weld metal regardless of the method used.

#### CONCLUSIONS AND RECOMMENDATIONS

1. The 716 filler material should continue to be used for the welding of the Pershing missile. This is because of the 0-10 percent higher yield and ultimate tensile strength level, and its apparent resistance to crack-susceptibility under severe restraint, as specified in the Army Ballistic Missile Agency specification, ABMA-PD-W-45A.

2. The vacuum-packed, high-quality shaved, HQ4043 filler is recommended for production under emergency conditions. This should be subject to the establishment of design allowables, for aft skirts and most probably G & C sections and acceptance by both Engineering and the Customer.

3. Both the 716 and 4043 filler materials produced acceptable, radiographically clean welds, per ABMA-PD-R27A specifications.

4. Less microporosity was obtained with the commercially available, vacuum-packed, high-quality and shaved 4043 filler material when compared to the specially ordered, high-purity and shaved 716 filler material.

5. The 4043 free-bend specimens had better ductility than the 716 specimens. For the Pershing missile applications, the ductility obtained in the 716 specimens is satisfactory.

6. Hardness transverses indicate that a harder weld deposit and more annealing of the 2014-T6 base-metal is obtained with the 716 filler material.

7. Metallographic examination revealed that ductility is reduced in the 2014-T6 heat-affected zone due to the precipitation of the brittle  $\text{CuAl}_2$  et al intermetallics at the grain-boundaries as a result of welding heat.

8. Due to the grain-boundary precipitation in the heat-affected zone, immersion time in chemical cleaning tanks must be limited to prevent intergranular attack in areas not protected by alcladding. Specifically, this applies to areas not protected by alclad and to a lesser degree, weldments in all alclad copper-bearing aluminum subassemblies.

9. The 716 filler material appears to be susceptible to microsegregation while 4043 does not.

10. Metallographic examination revealed very fine dendrites are formed in the weld metals. These are a result of rapid solidification which is controlled by both the rate of chill and the arc-energy input during welding.

11. The Reeves restrained test indicated that 4043 weld metal was somewhat more crack-sensitive than 716 under severe restraint and rapidly cooled with an air blast. Under severe restraint, and normal production cooling rates, no failures occurred in either material.

12. The Naval Research Laboratory sheet bulge test showed that weld joints, bead intact, made with either filler material, can be deformed without failure and that the flush 4043 weld joint was weaker than the similar joint welded with 716 filler wire. Additional work should be performed with this test as a weld-zone performance gauge.

13. A second vendor must be developed to supply high quality 716 filler material.

14. Carefully control the arc-energy input, and periodically examine tooling to insure adequate chilling, to minimize the formation of grain-boundary intermetallic compounds in the heat-affected zone of the weldment.

#### Bend Test Data

Specific data is recorded in Notebook No. 2251 and will be made available on request.

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## DISCUSSION

Mr. Jackson: Thank you, Mr. Hutchinson. I think it's sort of a delight to hear a real engineering paper this afternoon which as a whole was very successful. Almost everything worked all right, after some of the troubles we had this morning. You didn't even mention the word "hydrogen". I don't know what in the world happened. I think that ham luncheon that we had probably solved a lot of problems. But we have a few minutes here just for some comments and questions. Anybody want to start it?

Question: Were all these tests run in the as-welded condition or were any of them solution heat treated and aged?

Mr. Hutchinson: All of these tests were run in the as-welded condition. The only heat treatment that the specimens got was that which they received on testing at 600 degrees. I can class that as somewhat of a heat treat because the weld did get stronger than the base metal.

Question: What type of material did you use in your back-up bar for chilling and so forth?

Mr. Hutchinson: Yes, I'd say...possibly interesting too...we used a steel back-up bar. We noticed that we ran into a lot of gas---hydrogen gas entrapment---when we used copper. So we tried copper, stainless and carbon steel. Their thermoconductivities are significantly different but the tensile results between the copper and the steel were not significantly different, so we chose steel, which gave us a lower solidification rate and, as a result, less gas entrapment. It helped us quite a bit.

Mr. Jackson: Do we have another question?

Mr. Saperstein: I'd just like to make a brief comment, if I may. We have performed some work on the 716 and 4043. From the standpoint of fracture in the presence of a partial thickness crack and in the work that we have done both at room temperature and at minus 423°, the 716 is less tolerant than the 4043. This is talking about a weld that is approximately 6 percent silicon, in the case of the 716, and about 3 percent copper, as compared to roughly 3 or 4 percent silicon and somewhat lower copper in the 4043 weld. So, I am just saying this to interject an area where, for certain applications, it may not be desirable to use 716.

Mr. Jackson: Thank you. Here's a question here.

Mr. Platt: I wonder if you were working with alclad material?

Mr. Hutchinson: Yes, that's correct.

Mr. Platt: And I wonder, did you run any corrosion tests?

Mr. Hutchinson: Yes, we did.

Mr. Platt: Was it better or worse than the 4043?



Mr. Hutchinson: We did run some corrosion tests. Specimens were subjected to salt spray, 5 percent solution, 95°F, at about 96 to 98 percent dew-point. Due to the fact that the specimens were alclad, of course, there was no deleterious effect in the heat-affect zone. They were protected. There was some apparent attack on the weld, but nothing extraordinary. These were tested for some 244 hours. On micro sectioning, we did notice that we got a little bit of penetration which amounted to a rather insignificant amount---maybe a half a mil or so.

Mr. Platt: On the 716?

Mr. Hutchinson: On the alclad. But it seemed to be general type corrosion on the filler wires.

Mr. Jackson: We have time for one more question. Yes?

Miss Brennecke: In regard to 716 for the 1/2 inch material, you indicated you had higher properties by reheat treatment. Do you have any comparison of your room temperature values there with the 716 and with the 4043? The thing I had in mind was that there might be a possibility of showing a greater advantage with the 716 in a heavier plate because there is less intermixing.

Mr. Hutchinson: We don't have results as such, but the actual test flight of the article showed that the part failed where the weld occurred, and it obviously was much softer when welded with 4043, responding very poorly to heat treatment. It could be machined very easily, while the 716 demonstrated hardness comparable to that of the base metal.

Mr. Jackson: Thank you. I'll turn the meeting back to Jim Orr.

SPECTROGRAPHIC MONITORING OF INERT-GAS  
SHIELDS FOR ATMOSPHERIC CONTAMINANTS

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## ABSTRACT

The feasibility of monitoring inert-gas metal-arc welding-process shields for contamination by hydrogen, oxygen, and nitrogen by using special spectrographic techniques was studied. These techniques are adaptable to continuous monitoring of production welding. Both nonconsumable and consumable metal-arc processes were considered. The welding was performed on commercial 6061-T6 aluminum and a pure aluminum standard prepared by a consumable vacuum-arc melting technique.

The image of the arc was focused on the external limiting aperture of the spectrograph to mask the glowing electrode and the work metal. The spectrograph slit was illuminated with integrated light. The arc was maintained in a fixed position, and the work metal was moved to accommodate the present spectrographic equipment.

The spectra were recorded photographically in the 6200-to 8800-A region. The analytical lines, and the 8216.5-A nitrogen line. The 7147.5-A argon line was used as the internal standard line. A single reference line was used because of the possibility of using a four-cell readout system in the future.

Changes in contamination levels due to moving air, shield-gas flow rate, and moisture were studied. Appreciable differences were found in the purity of commercial argon and helium. In the consumable process, contamination in the shield gas was reduced considerably when the upper wire guide in the torch was blocked with a flow of inert gas.

In most of this study a mixture of 50 percent argon and 50 percent helium was used as the shield gas. The use of pure argon and pure helium was also briefly studied. The sensitivity of the contaminating gases was less in argon than in the argon-helium mixture at the same amperage. In addition, argon caused a very high background. The helium arc was very sensitive to contaminants; the pink color of the arc faded, and the intensity of the helium lines recorded spectrographically decreased as small quantities of argon or the atmospheric contaminating gases were added. This indicates that this arc is carried largely by the ions of foreign gases. Atmospheric contaminants and filler wire caused some cooling of the argon-helium arc.

The standard deviation of the oxygen/argon and hydrogen/argon ratios was excellent -- better than that found in most standard spectrographic procedures. Different current levels had little effect on the oxygen-argon ratio, as indicated by the same calibration curve for three current levels. The similarity of the calibration curve for wire alloy 4043 to the curve for the arc, only without filler wire, indicates that matrix effects are much smaller than expected. This is also indicated by the similarity of the calibration curves for each of the four wire alloys.

## INTRODUCTION

The steadily growing requirements in the field of welding are requiring a better knowledge of the art and science of welding and better quality control. Since a welding arc can be thought of as a high energy excitation source, it would appear feasible to apply emission spectrochemical techniques to determine the atmospheric contaminants in inert gas welding shields.

This paper discusses the application of emission spectroscopy to the monitoring of the inert-gas metalarc welding shields for the atmospheric gas, nonconsumable) and the MIG (metal inert gas, consumable) arcs were studied, but with the emphasis on the former process.

## EQUIPMENT AND MATERIALS

The spectrograph was a Jarrel-Ash 3.4-meter Ebert mount instrument, model JA-7120, with a 15,000-line/inch plane grating blazed for 4,000 Å in the first order. A Jarrel-Ash comparator microphotometer, model 2100, was used for densitometric measurements in the plates.

The photographic emulsions used were I-N and IV-N. The IV-N is a higher-contrast, slower-response emulsion than the I-N, but sufficient light energy was available to use the I-N emulsion in the near-infrared region. This emulsion was not used at all times, however, because it was not readily available. Only 2-to 3 second exposures could be made with the I-N emulsion, except when a relatively dense, neutral filter was included in the light path. The longer exposure times, 15 to 30 seconds, which were possible with the IV-N emulsion made small variations in time negligible.

The power source was a Miller model 360P AC-DC welding power unit. Some preliminary experiments were conducted using the Jarrell-Ash custom VariSource as the low-voltage DC arc source and a Stallwood jet (7,8). The Stallwood jet is a small, controlled atmospheric chamber often used in spectrochemical analysis.

The shield gas used in most of this study was 50 percent argon-50 percent helium. Argon and helium were used for some comparison studies. Very pure argon, 99.999 percent obtained from the Linde Company, was used in order to have a reference for gases of known purity.

A Linde HW-10 Heliarc water-cooled torch and an Aircomatic model C automatic unit were used for the nonconsumable metal-arc welding processes, respectively. The Aircomatic Unit was later modified for use as a wire guide and wire speed control in the TIG process.

Four aluminum alloy wires were used: compositions 4043, 5556, and 2319, and a copper-clad aluminum wire.

The rotating positioner, used as the work metal, was designed and built from 5-1/2-inch-diameter, 3/8-inch-wall aluminum alloy 6061-T6 pipe. The positioner was driven by a variable-speed motor coupled to a variable-speed torque converter. The shaft was threaded and turned in a nut, so that the weld bead did not overlap as the drum rotated. Heavy silicon rubber insulating mounts were found to be satisfactory.

A degassed aluminum cylinder was prepared to eliminate possible sources of contamination, impurities, and gases in the 6061-T6 alloy. This cylinder served as a standard. It was cast by a consumable-electrode vacuum-arc melting technique at a pressure of about  $5\mu$  of mercury. The casting was machined, centered-drilled, and mounted on a shaft as described above. After use, the filler aluminum and the oxidized metal were removed by "machining down" the positioner to new degassed metal.

The flow rate of the inert shield gas and of gas mixtures of known contamination was measured by four calibrated rotameters. Known quantities 0 to 2000 ppm, of contaminants were added in the shield gas line about 10 ft from the torch. The rotameters were calibrated for each gas and gas mixture used. The known 50 percent argon -- 50 percent helium mixture contained 1 percent each of the contaminating gases: oxygen, hydrogen, and nitrogen. The tanks were occasionally stored horizontally because the heavier fractions in gas mixtures are reported to slowly concentrate in the bottom.

#### EXPERIMENTAL PROCEDURES

The basic experimental layout for the TIG (tungsten inert gas, nonconsumable) process is shown in Figure 1. The positioner (work metal) can be adjusted to keep the arc in proper optical alignment. The experimental layout for the MIG (metal inert gas, consumable) process was similar, except that the torch and heavy head were mounted in a fixed position above the positioner.

The imaging configuration for the TIG arc is shown in Figure 2A. The light from the arc is passed through a lens and is reflected by an angle mirror to the external limiting aperture of the spectrograph. The image of the arc is focused on the aperture. The light then passed through the condensing lens, so that the spectrograph slit is filled with integrated light. The ratio of the image size to the arc size was approximately 1:1.

The position of the MIG arc image on the limiting aperture is shown in Figure 2B. This configuration was used because radiation from the metal spray in the arc was expected to produce strong background. However, reproducing the position of the arc in this configuration was difficult, and this positioning of the arc was found to be very critical with respect to reproducibility and sensitivity. Later work indicated that possibly the MIG arc can also be imaged directly in front of the slit.

Standard ASTM procedures were used for photographic processing, plate calibration, and photometry (Reference 6).

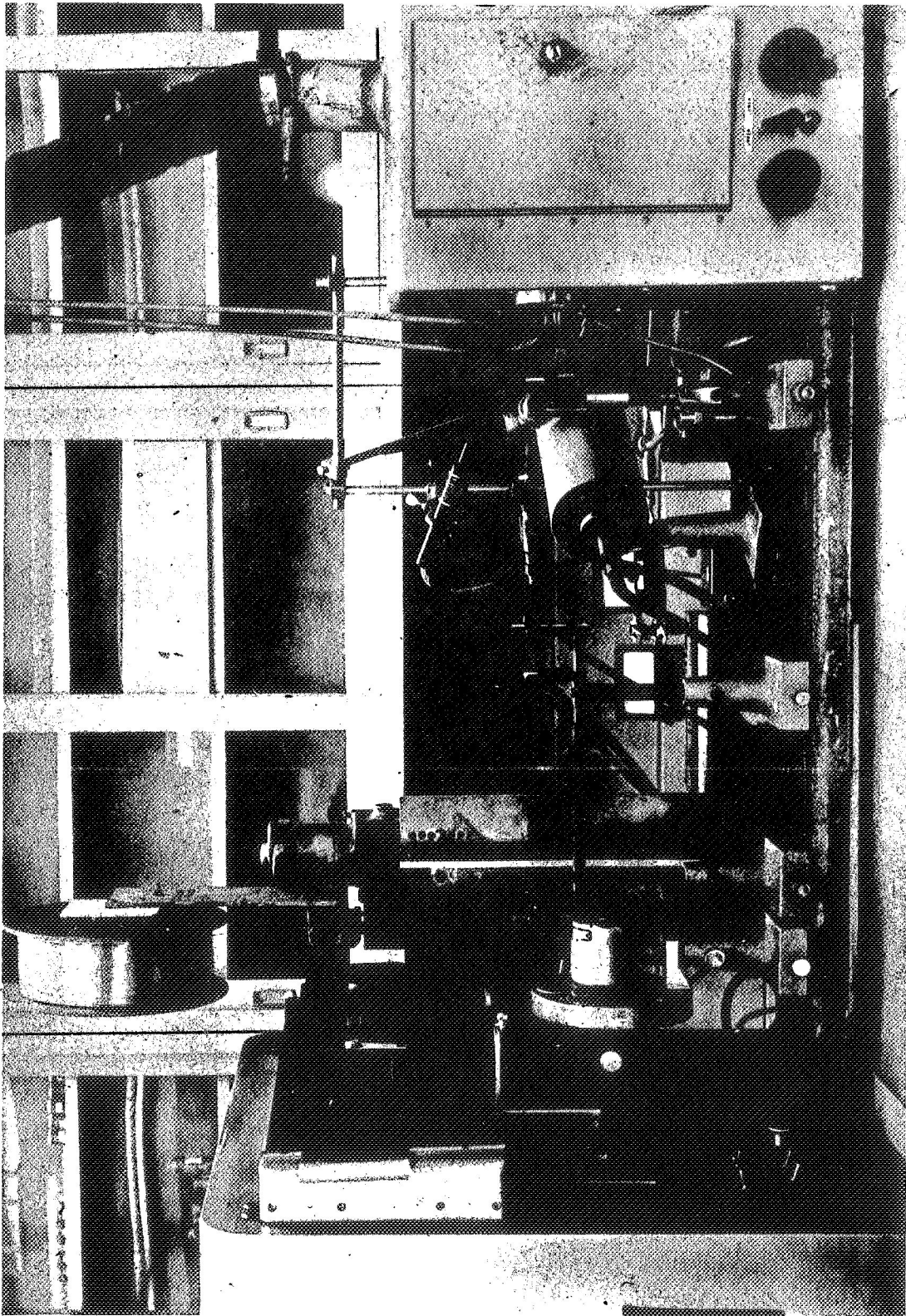


Figure 1. Experimental Layout for The TIG Torch

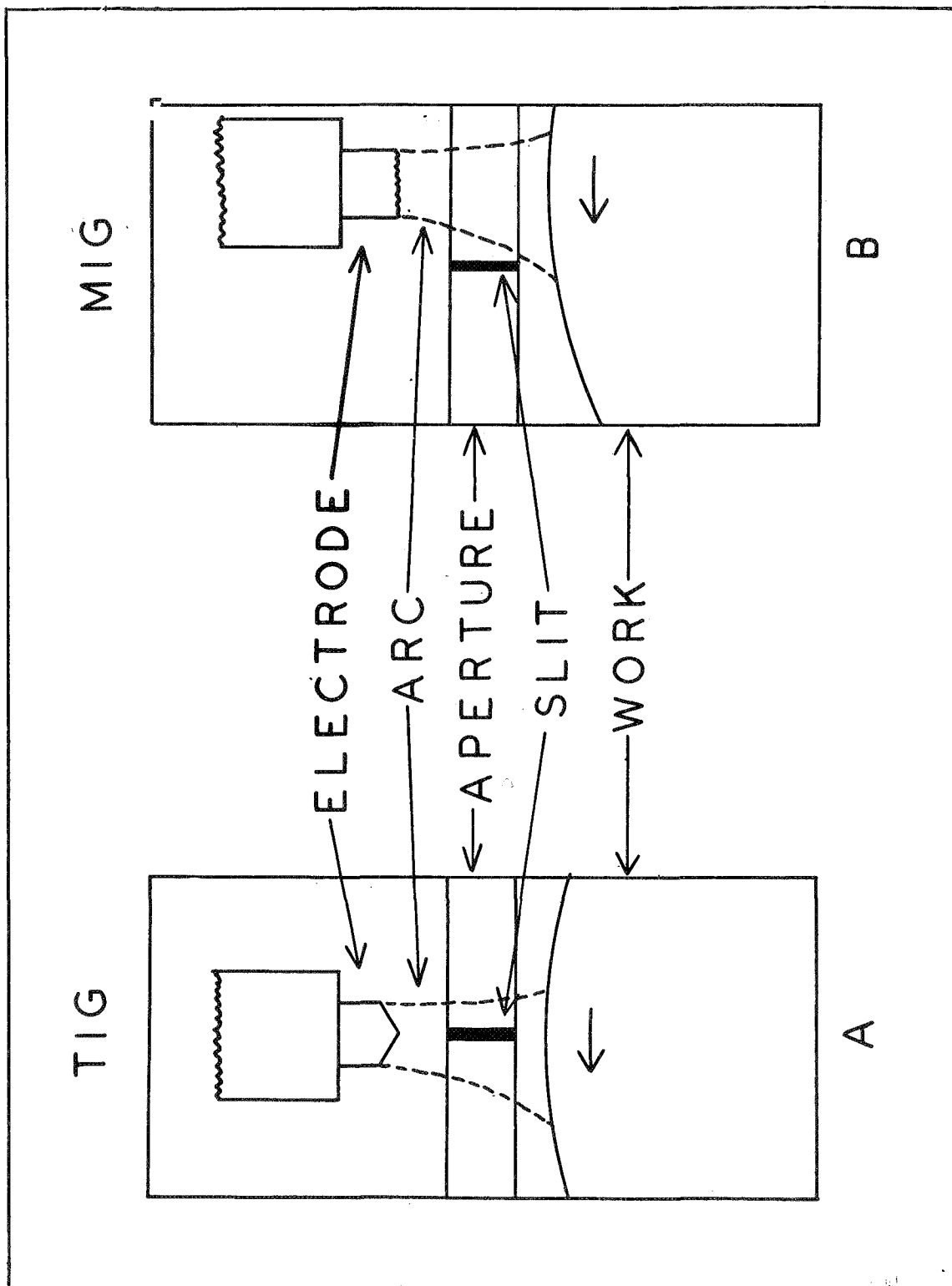


Figure 2. Imaging Configuration

Calibration curves, which are necessary for the analysis of unknowns, were prepared by addition of 0 to 2000 ppm of contaminating gas to the inert shield gas. The general procedure was to arc two or more blanks (i.e., no contaminant gas added), arc known amounts of contaminating gas from 20 to 2000 ppm, and then arc two or more additional blanks.

Calibration curves were prepared for each contaminant with each wire alloy present and with no wire alloy present. These curves were prepared for these different conditions because the slopes of the curves were expected to be different due to the cooling or matrix effects and to residual contamination in the wire alloy. A typical calibration curve for oxygen is shown in Figure 3. The level of residual contamination was determined from the calibration curve by the method of successive approximation (Reference 1) or by the point-of-intersection method. This residual contamination may be due to turbulence or to impurities in the shield gas, the working metal, and the wire alloy. One tank of shield gas was found to contain approximately 1000 ppm of oxygen.

## RESULTS AND DISCUSSION

The spectra of the shield gas and the contaminating gases were studied and the analytical lines selected. Several sources of possible contamination and their effects on the spectral response to the level of contamination were examined. The calibration or working curves, which are necessary for a monitoring procedure, were prepared and some of the factors that may effect the slopes of these curves were studied.

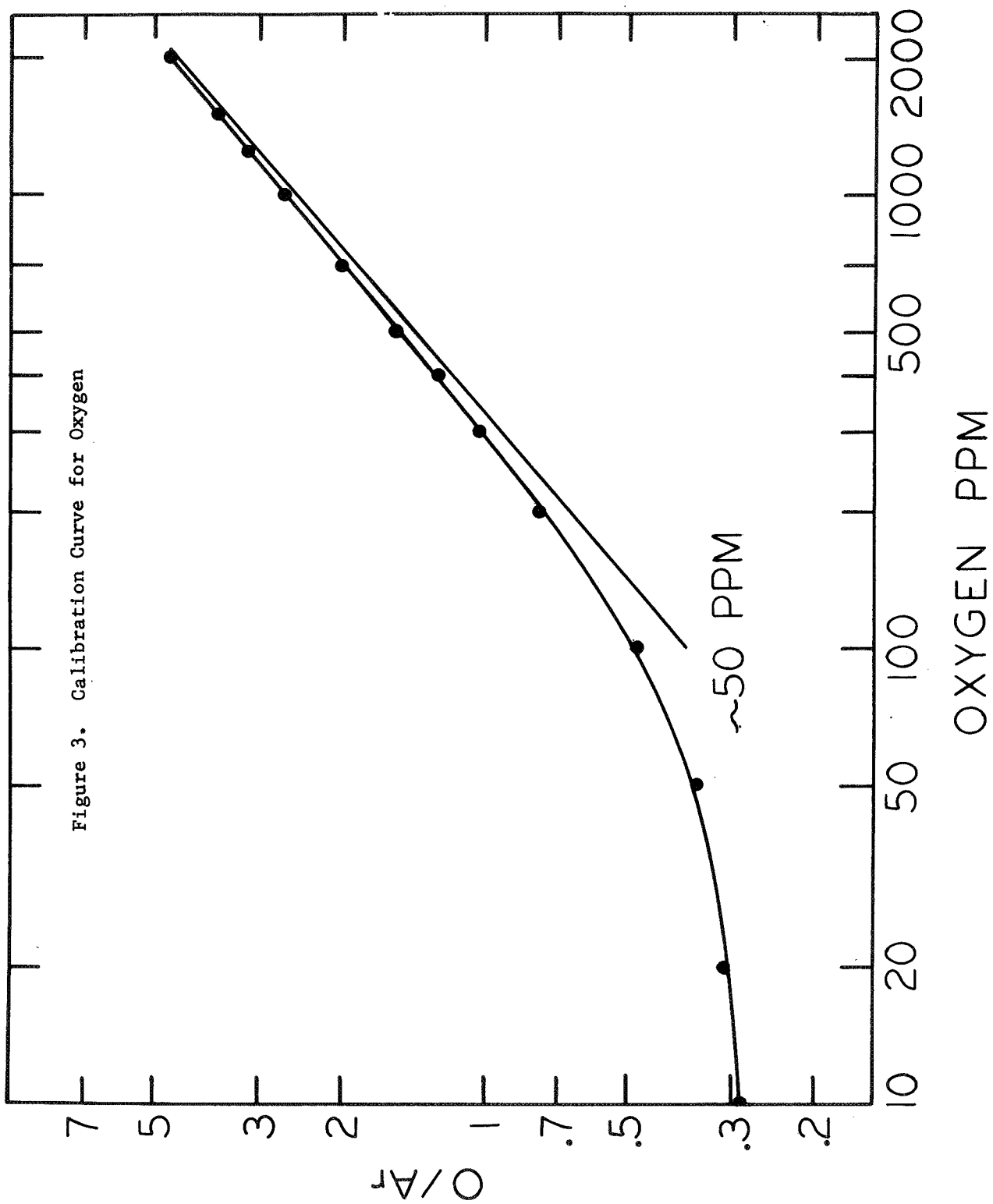
### Spectra and Analytical Lines

The spectra in the region from 6200 to 8800-A were studied, since this region contains the analytical lines for oxygen and hydrogen. Nitrogen lines are present in the 4000-A region, but their excitation potentials (13.7 ev) are higher than those for the lines in the 8000-A region (~11.8 ev).

Although some of the lines in this region have already been studied for conventional spectroscopic procedures using low-current arcs, additional study was required since atomic spectral lines do not behave in the same manner under all conditions. The high-current arc used in this study may cause the line contour to change to a broadened, more diffuse line (Reference 5).

The analytical lines selected were: oxygen, 7771.9 A, (10.73 ev); hydrogen, 6542.8 A, (12.09 ev); and nitrogen, 8216.5 A, (11.84 ev). The 7147.5-A argon line (13.3 ev) was used as the internal standard line. A single reference line was used in view of the possibility of using a four-cell readout system in the future. The argon 7891.1-A line, used by Fassel and co-workers (Reference 2, 3, and 4) in their procedures for oxygen in metals, and the 7272.9-A line were found to be unsatisfactory before the 7147.5-A line was adopted. The nitrogen 8216.5-A line was found to have better characteristics than the nitrogen 8680.4-A line.





### Shield-Gas Flow Rate

A shield-gas flow rate of 20 cfh was used in most of the studies with the TIG process. This flow rate was selected by visual inspection of the weld area after using a 150-amp AC arc. Figure 4 shows the effect of flow rates from 5 to 45 cfh on a 150-amp AC TIG arc using a 5/16-inch ID nozzle, by measuring the change in oxygen contamination. A similar curve was obtained with a 150-amp DCSP arc. An examination of the figure indicates that better protection was obtained at 25 to 30 cfh. At 4 cfh the work metal was very black and deeply pitted. With the DCSP arc this effect on the work metal was similar to but less pronounced than that for the AC arc.

Figure 5 shows the effect of shield-gas flow rate in the MIG process using a 3/4-inch ID nozzle. The possible increase in contamination due to turbulence at the high flow rates was not observed.

### Incoming Wire Guide

A possible course of contamination in the MIG process is the air that can be drawn through the incoming wire guide by the partial vacuum created by the flow of shield gas. A brass elbow, drilled to admit the wire, was fitted over the top of the wire guide. Sufficient pressure was used so that the inert gas flowed through the hole in the fitting as well as down the wire guide. The relative change in the levels of contamination with a 30-cfh shield-gas flow rate is illustrated in Figure 6.

### Simulated Breeze

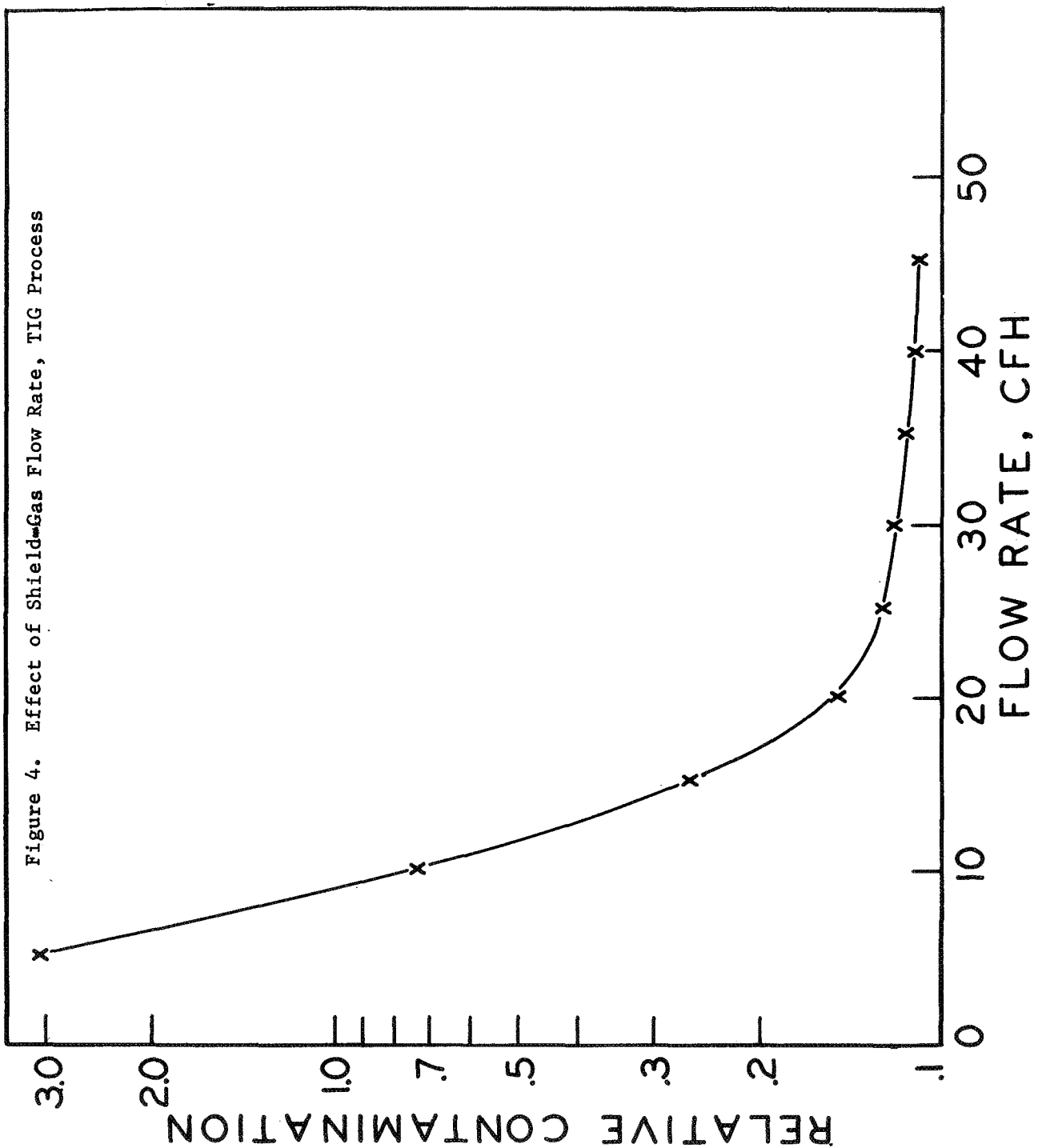
Figure 7 represents the relative change in the contamination levels in the MIG arc with a simulated breeze of 325 fpm. The "fill" changed from a relatively smooth and solid bead to one with a very rough and porous surface.

The relative level of contamination, as expected is a function of breeze velocity. This is illustrated in Figure 8 for the TIG process using a 150-amp DCSP arc. A 5/16-inch ID nozzle was approximately 1/4 inch from the work metal. The shield gas offered considerably more protection at 30 cfh than at 20 cfh. A velocity of 900 fpm blew out the arc shielded with a flow rate of 30 cfh.

### Moisture Effects

In the preparation of the preliminary calibration curves, blanks were arced at the beginning and the end of a series containing known quantities of contaminants. It was observed that the contamination level in the blanks was often less at the end of the series than at the beginning. This suggested that moisture had been absorbed on the cold work metal, torch nozzle, or both.

A series of spectra, starting with cold work metal and torch, were prepared during a 12-minute period by using the moving-plate technique. The decrease in the relative contamination as illustrated by oxygen (Figure 9) indicated that moisture was being driven off the work metal and/or the ceramic nozzle by the heat of the arc.



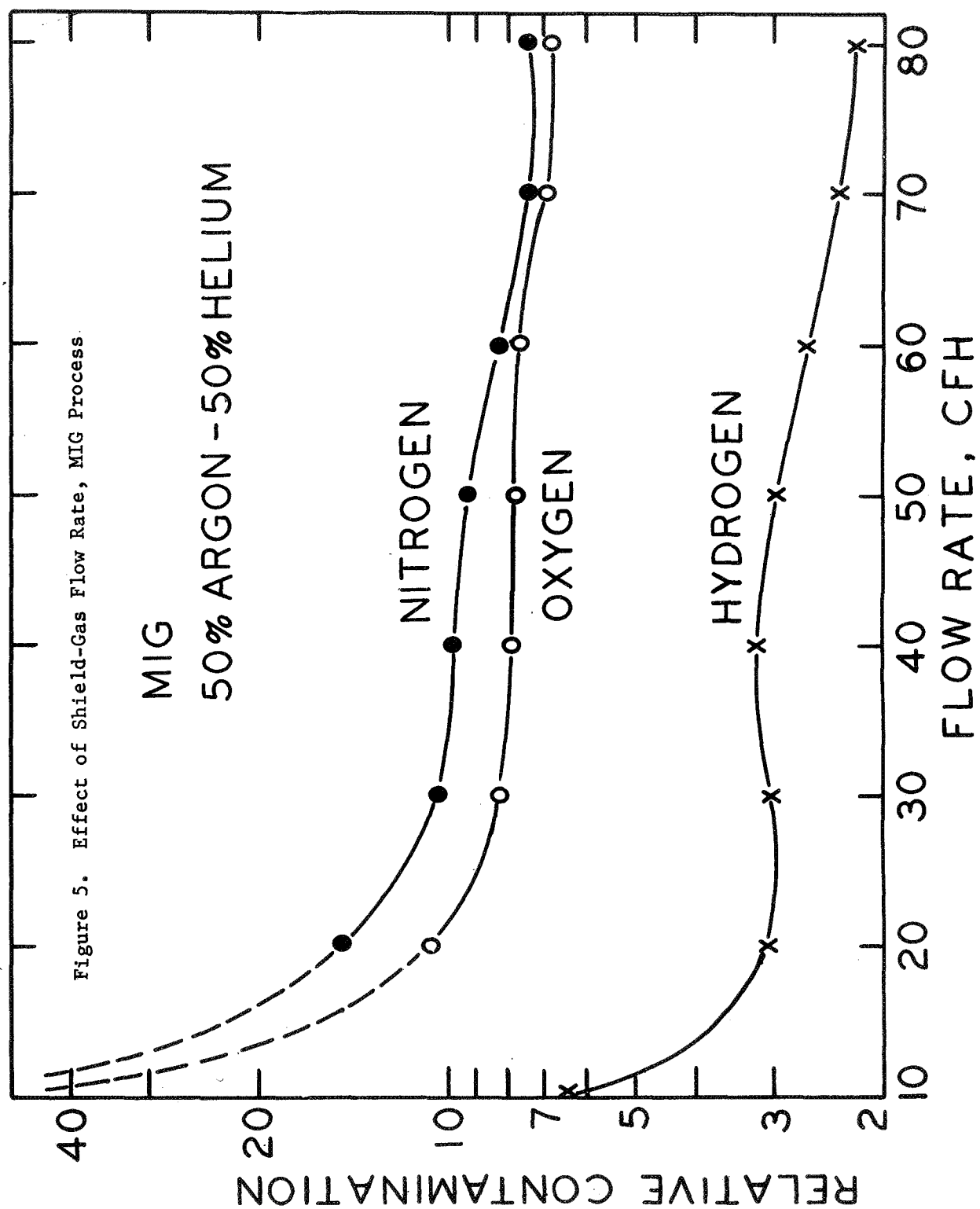


Figure 6. Effect of Shielding Incoming Wire Guide°, MIG Process

 NOT SHIELDED  
 INERT GAS SHIELDED

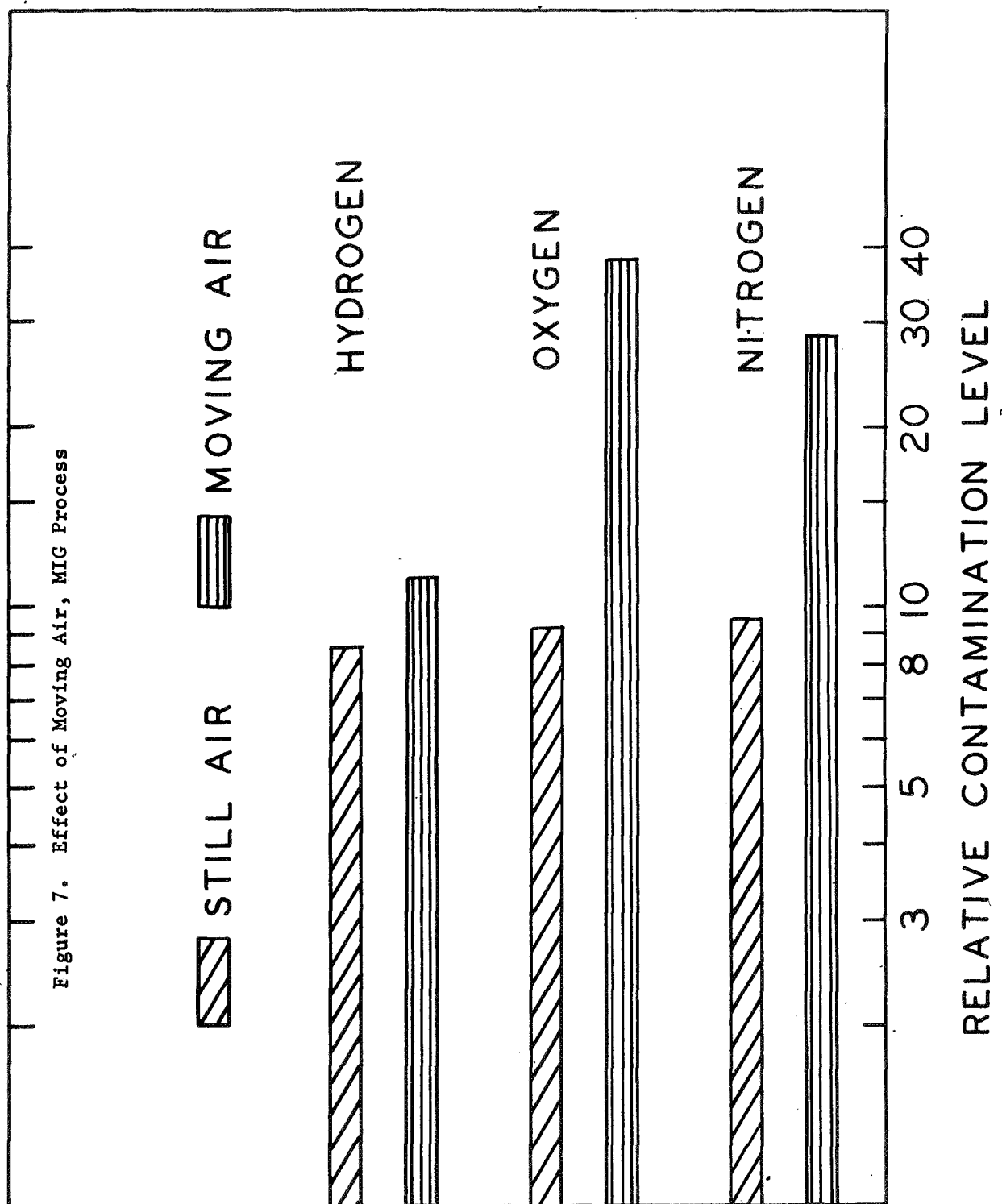
HYDROGEN

OXYGEN

NITROGEN

3 5 8 10 20

RELATIVE CONTAMINATION LEVEL



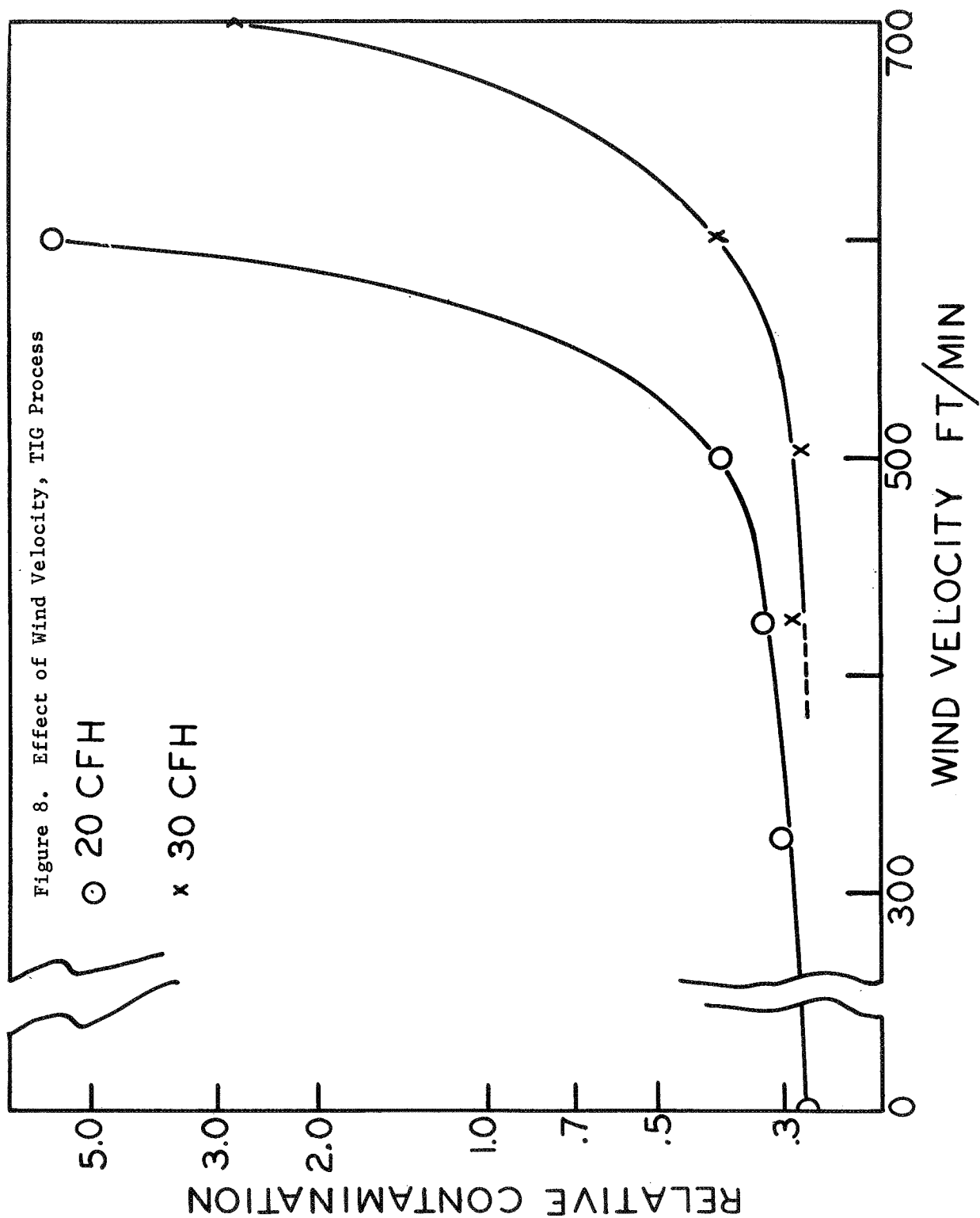
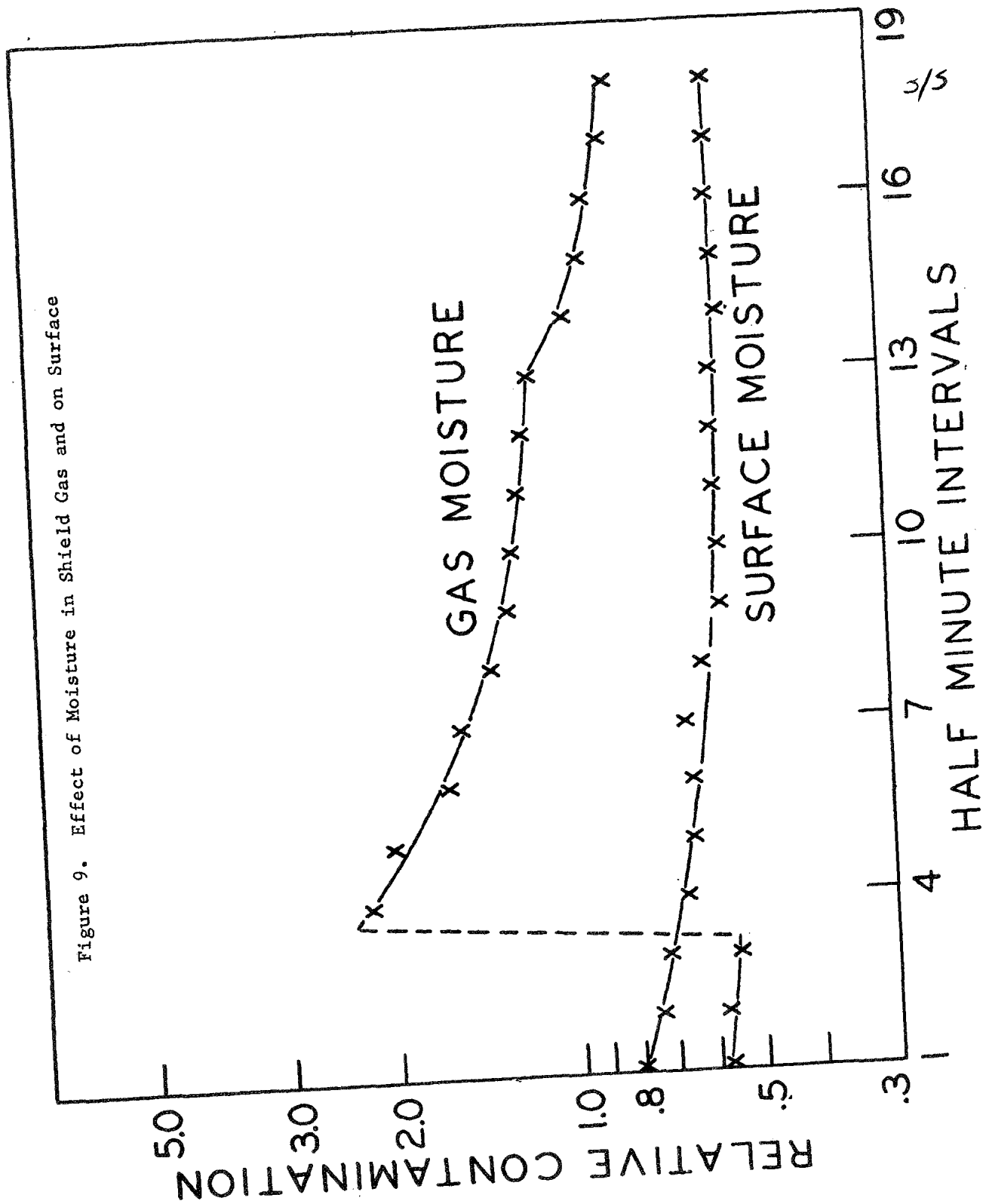


Figure 9. Effect of Moisture in Shield Gas and on Surface





The effect of moisture in the shield gas or in the gas line was illustrated by injecting 0.05 ml of water into the shield gas stream about 20 feet from the torch and recording the spectra for oxygen (Figure 9) by the moving-plate technique. The sudden rise is due to the saturated gas reaching the arc, and the gradual decrease represents the moisture being desorbed from the interior wall of the tubing.

Occasionally very high results obtained in the 20- to 100-ppm range were observed, especially when the torch had not been used for a few days. Possibly desorbed moisture from the tubing walls and rotameter was carried into the arc. When these surfaces were purged with dry gas before use, high results were not obtained.

### Calibration Curves

In a spectrographic procedure, calibration curves are prepared keeping as many parameters such as current, arc length, composition of the matrix (major elements present), and time of exposure, as constant as possible. The calibration curves are used as the references to determine the unknown concentrations. If the intensity of a spectrum increases proportionally as the concentration of the test element increases, then a calibration curve (Figure 3) can be prepared.

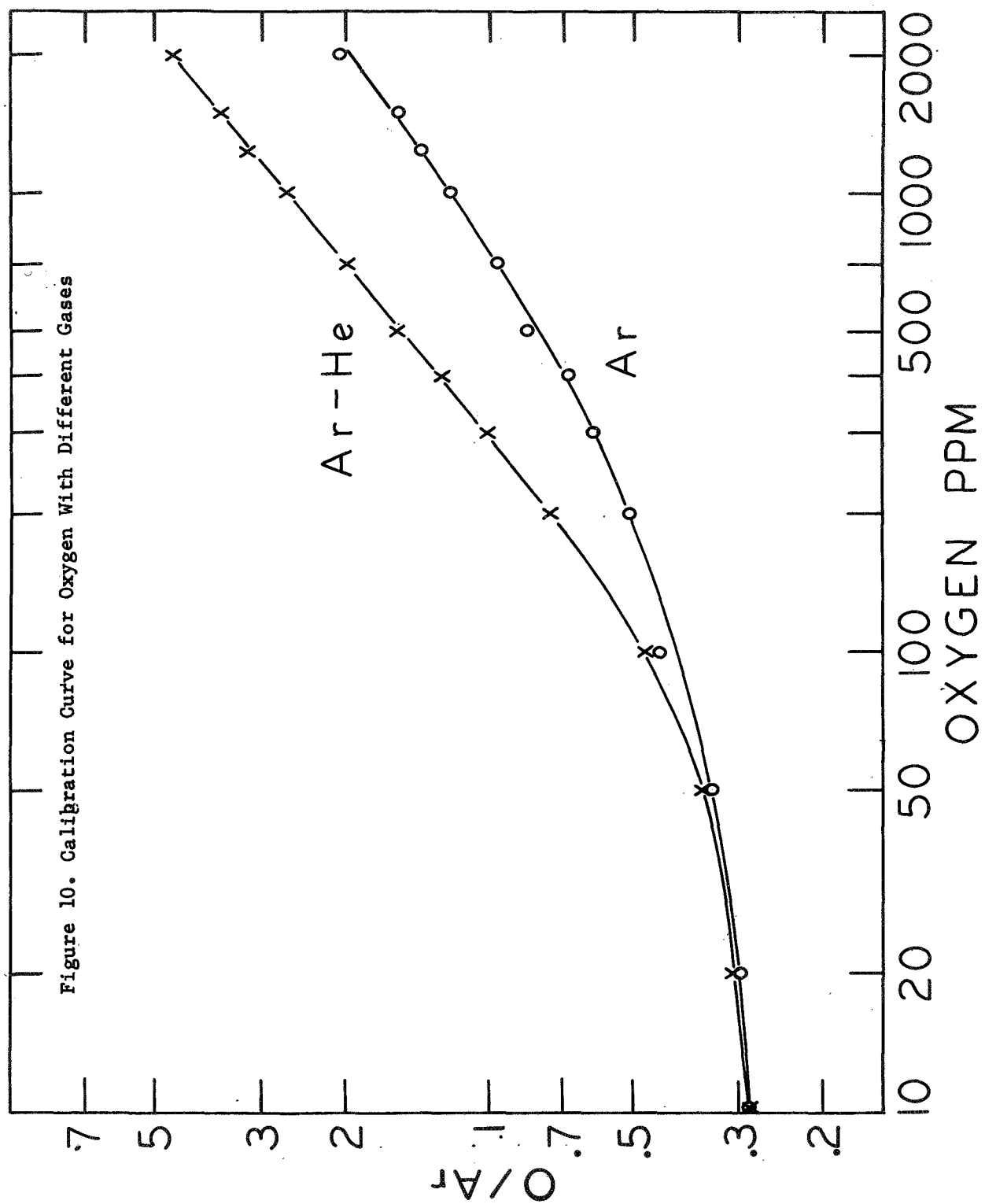
Calibration curves for oxygen, hydrogen, and nitrogen were prepared with 50 percent argon- 50 percent helium and with argon as the shield gas. The nearly linear response as the concentration of oxygen increased indicated that an analytical procedure was possible. The slope of the curve indicates the sensitivity of the shield gas to the contaminant. The lack of response at the lower concentration shows that residual contamination was present, i.e., about 50 ppm of oxygen for this tank of gas and materials used. This value varied from tank to tank of gas.

### 50 Percent Argon-50 Percent Helium

Figure 10 shows the calibration curve for oxygen in the TIG arc with 150-, 100-, and 50-amp DCSP arcs using 50 percent argon -50 percent helium. Thus intensity ratios were the same at each current. However, as expected, for the 100- and 50-amp arcs more time was required to obtain equivalent line darkening on the spectrograph plates.

### Argon

The sensitivity to atmospheric contaminants was less when pure argon was used (Figure 10) than when argon-helium was used as the shield gas. Calibration curves for 150-amp DCSP and AC arcs were prepared. No difference was noted in the slopes. The considerably higher background on the spectrographic plates when argon was used is probably due to recombination energy. This effect is much less in the argon-helium mixture because of the dilution by helium. With argon, the ceramic nozzle became very hot, which was not observed with the argon-helium shield gas.



## Helium

A few experiments were performed with the TIG process with pure helium as the shield gas, a 150-amp DCSP arc, and a gas flow rate of 30 cfh. A short electrode gap, 1/16 to 3/32 inch, was used. The helium arc was profoundly affected by the presence of the other gases, such as argon and the atmospheric contaminating gases. The pink color of the arc faded as the concentration of the other gases increased, and the color returned when the foreign gases were removed. This effect was readily followed on the spectrographic plates, i.e., as the lines for the contaminating gas became stronger, the helium lines decreased markedly in intensity. This indicates that the arc is being carried largely by the foreign gases, which have much lower excitation potentials. Very high sensitivity to the atmospheric contaminating gases was also indicated. When helium was used, the spectral lines for oxygen, hydrogen, and nitrogen were much darker at the same concentrations than when argon-helium or argon alone was used.

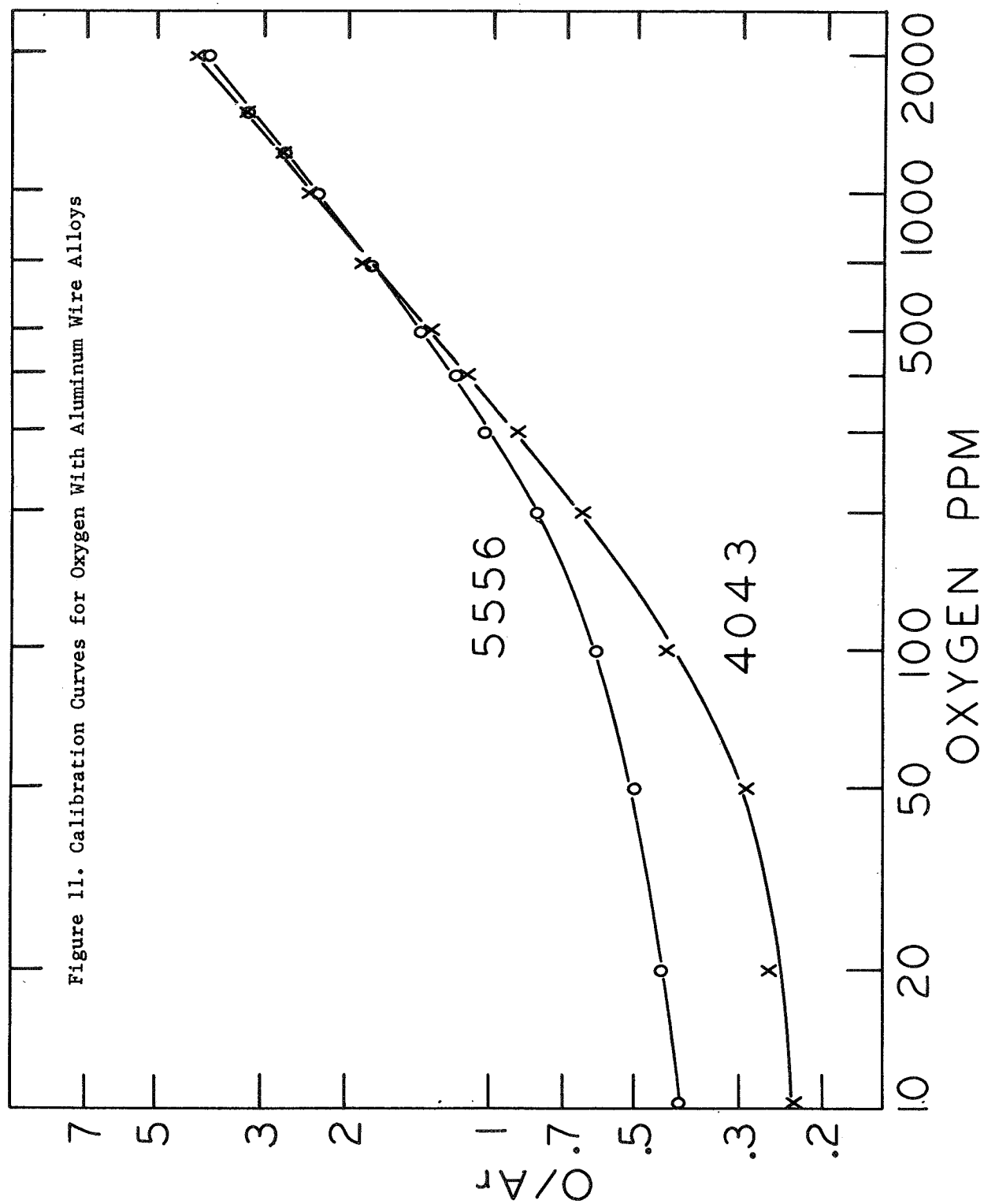
Only three helium lines, 6678.5, 7065.2, and 7281.4 Å, appeared in the region from 6200 to 8800-Å. The lines are intense and much too heavy for densitometry. If a readout system is desired, a neutral filter could be used in front of the receiver for the helium line that is used as the internal reference line. However, because of the very high excitation potential, these lines vary in intensity when any foreign gas with a lower excitation potential is present. If some gas other than that of analytical interest should be present, false readings would result. Probably a small and constant amount of argon could be added to the helium in order to have an internal standard.

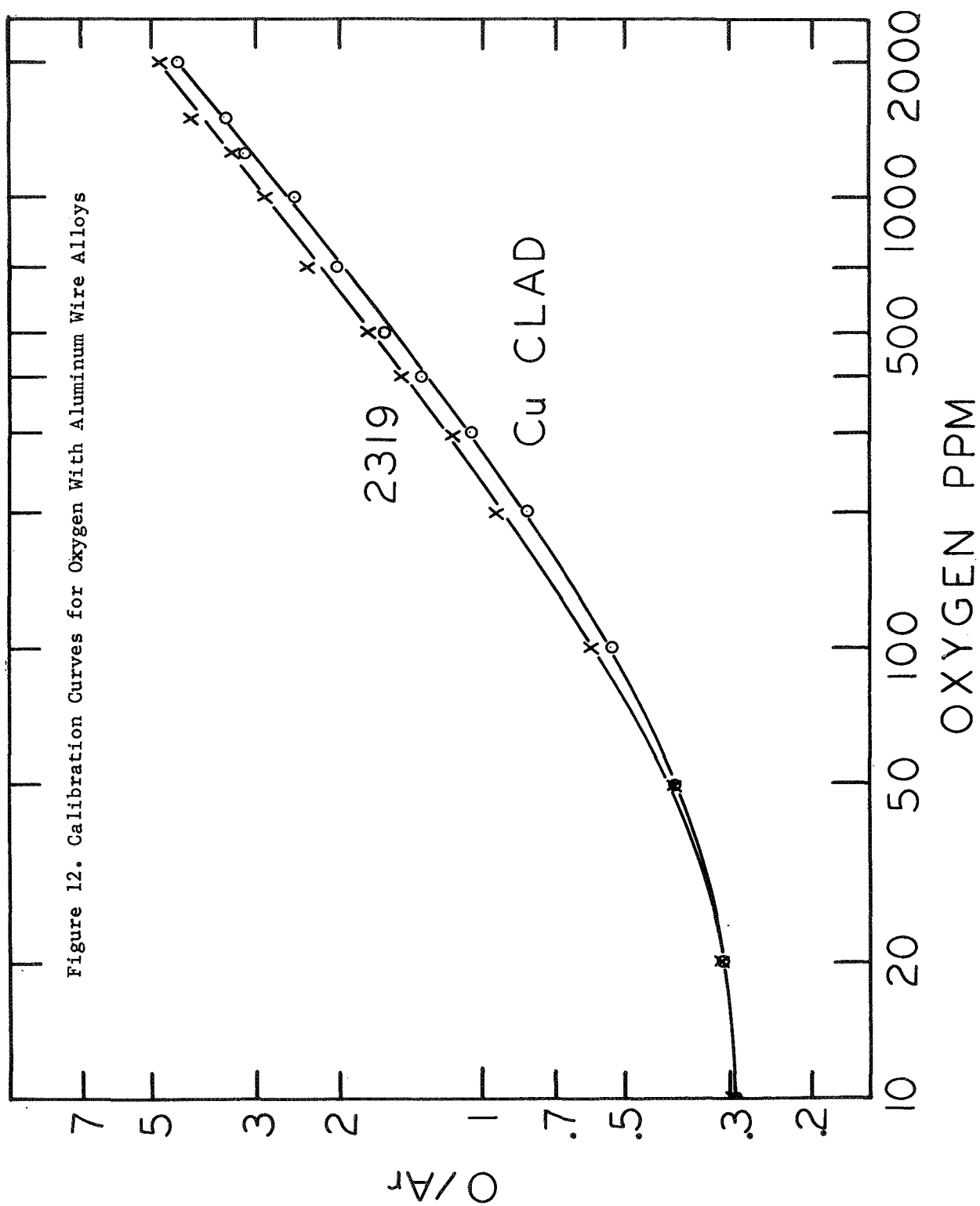
The effect of impurities on the shielded area after cooling was pronounced. With no contamination added, the surface was very clean and mirrorlike in appearance. When 200 to 300 ppm of contaminant was added, the surface was tarnished. After 400 ppm was added, the surface was darker and rough. This change increased progressively, until in the 1250- to 2000-ppm range the bead area was very dark, rough and pitted.

## Aluminum Wire Alloys

Calibration curves were prepared for the TIG process for each of the aluminum wire alloys because of the expected cooling and matrix effects on the arc. A 150-amp DCSP arc was used. The speed of the work metal was approximately 5-1/2 ipm, and the wire feed rate was 24 to 30 ipm. The calibration curves for oxygen with wire alloys 4043, 5556, 2319, and the copper-clad aluminum wire are shown in Figures 11 and 12.

These curves were prepared with the same tank of shield gas as that used for the curve shown in Figure 10. The residual oxygen contamination associated with the 4043 wire was approximately 50 ppm, which is approximately the same as that associated with the argon-helium arc when no filler alloy was present. Thus it appears that this wire contributes very little, if any, oxygen contamination to the arc.





The residual oxygen contamination associated with the 5556 wire was approximately 100 ppm. However, the slope at the upper end of the calibration curve is similar to that for the 4043 wire. Thus the difference in the composition of these two wire alloys appears to have no significant effect on the oxygen/argon intensity ratio. A slightly longer exposure time was needed to obtain equivalent line darkening with the 5556 wire than with the 4043 wire. The curves for the 2319 and the copper-clad wires (Figure 12) were also found to be very similar to the calibration curve when no filler alloy was present.

Changes in the intensity of the argon 7147.5-A line, the internal standard line, indicated that atmospheric contamination in the shield gas, moisture, and the different wire alloys have a cooling effect on the arc. The intensity of this line consistently decreased when 300 to 400 ppm of oxygen, hydrogen, and nitrogen was added to the shield gas. The presence of moisture in the shield gas reduced its intensity. When filler alloys were introduced into the arc, the intensity also decreased. The 5556 alloy wire decreased the intensity much more than the other alloys. An examination of the calibration curve for oxygen indicates that the major portions of the curves for the work metal (Figure 10) and the 4043, 2319 and the copper-clad wires (Figures 11 and 12) are nearly identical. This indicates that the wire alloys had much less effect on the oxygen/argon intensity ratio than was expected.

#### Precision

The TIG arc was very stable with the work metal only and also with the four wire alloys. With the 5556 alloys, the arc did appear less stable and numerous bright flashes of light were observed. When the work metal was coated with a heavy layer of oxide and when the shield gas was contaminated, the arc was less stable.

In order to evaluate precision, usually nine spectra were taken consecutively for each experimental condition. One hundred ppm of contaminant gas was added for the lower concentration in order to have spectral lines intense enough for convenient densitometry. The exposure time for each wire alloy and work metal was approximately 10 seconds. The wire alloy feed rate was 24 to 30 ipm.

The standard deviation was calculated and is summarized in Table I. The precision was very good--better than that obtained in conventional spectroscopy. There was greater variation for the same points from day to day because of the variation in adjusting the rotameter values. If there was much variation in the wire compositions, it was not revealed by these studies. For the blackened rough work metal the precision was also much better than expected. Also, the expected increase in the intensity of the oxygen lines was not observed.

Table I. Standard Deviation for Oxygen and Hydrogen  
in the TIG Arc (150 amp, DCSP).

	<u>Oxygen, ppm</u>		<u>Hydrogen, ppm</u>	
	<u>100</u>	<u>300</u>	<u>100</u>	<u>300</u>
No wire	2.6	2.0	2.6	3.1
4043 wire	2.9	3.7	4.0	2.2
5556 wire	4.4	4.4	6.1	4.7
2319 wire	3.0	2.8	4.3	5.8
Copper-clad wire	3.7	4.1	2.9	4.1
<hr/>				
Residual Contamination				
No wire, clean surface	2.1		3.6	
No wire, prearced (black) surface	2.1		4.4	

#### SUMMARY

This paper summarizes some of the observations that have been made as the result of studying the feasibility of monitoring inert-gas shields for atmospheric contaminants. The analytical lines for the atmospheric contaminants, oxygen, hydrogen, and nitrogen became proportionally more intense as increasing quantities of these gases were added to the inert shield gases. This and the reproducibility of the points on the calibration curves indicate that the atmospheric contaminants can be monitored in the TIG process.

Changes in contamination levels due to such sources as moisture, moving air, and shield-gas flow rate were studied. Contamination was reduced considerably when the incoming wire guided for the consumable electrode was blocked with a flow of inert gas. The level of contamination was found to be appreciably greater in the MIG than in the TIG process. The effect of contaminants added to the shield gas was briefly studied in the TIG process. The helium arc was found to be profoundly affected by the presence of other gases. Appreciable differences were found in the purity of commercial argon and helium.

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#### ACKNOWLEDGEMENTS

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The authors wish to acknowledge the help and suggestions of David C. Brown and John F. Rudy, Metals Division, IIT Research Institute.



## DISCUSSION

Mr. Jackson: I don't know which one of us is going to be the biggest liar before this afternoon is over, but I only had six cows and I was milking two. They were prize production cows and we milked them four times a day. I think that will top a couple of them. All right, let's get on into the discussion. This is a kind of thing that we need as far as welding data is concerned. One of the things that I am very happy to see in some of his relationships here is a nice, smooth curve. Not at all like welding curves but a lot like the scientific curves that you can get from scientific data.

Dr. Grove: That's because I'm an analytical chemist and not a physical chemist.

Mr. Jackson: Let's start now. Anybody have a question, so that we can start in on this?

Mr. Lenamond: I'm curious about your technique in analyzing the gases or the arc on a manual, coated electro-arc. Do you think that you could analyze the transfer of the material in a coated electrode arc?

Dr. Grove: Now when you say a coated electrode arc, are you referring to the metallic species that you have there, or the non-metallic species?

Mr. Lenamond: No, the metallic. In other words, if you've got nickel or if you've got sulphur or anything transferring across the arc, could you analyze this?

Dr. Grove: I haven't tried it yet, but I do not see why not unless you have too much blackbody radiation. Now you see, here is one of the things that is bothering me on this thing now. Can I have this board, please? Look at it this way. Spectrographically, if you put a sample in an electrode, put another electrode above it, and arc it, you see what is in that sample by looking at the arc, photographically. I don't see why you should not see the material in this electrode that you are talking about. In other words, if this is a plate or a work metal, if it happens to be your anode, if this is your tungsten electrode at the top, and we'll say this is your arc, if you are feeding your filler wire in a position like this, according to spectroscopic theory, some of the species, due to the reactions taking place here, should be up here in the arc and you should see them. This gets into the next question. Some of the things I've observed in the last couple of years bothers me about this, and I am not too sure myself yet whether the welding arc with its high amperes compared to the 5 to 10 amp spectrographic arc is behaving the same or not. I'm going to try to pull somebody's leg, like a welding research council, or someone, for a little funds to look at this particular thing. I've looked at it a little bit already by focusing the arc itself on the slit so that I'm seeing the mechanism that's taking place all the way from here down through here. I've got to examine this a little bit more and study this arc, itself, to see where the species excitation is taking place, before I can answer your question for sure. But from the spectroscopic standpoint,

I think it ought to be there. Now, there may be another reason for it because under these conditions we have an extremely high temperature arc; we may be above the ionization potential of all these metallic type atoms in there, and if we are, we're not seeing any atomic lines. Then we would have to look for ionization lines, which, in the particular region I have been working in, are very scarce. Theoretically, from the spectroscopic standpoint, we should be able to see them, yes.

Mr. Jackson: Thank you. There's a question here?

Mr. Hackman: As you pointed out, you have the advantage, I think, on most of us, or at least myself, because I'm not versed in this art. Is the quantitative measurement that you get based on excitation of the particular gas that you see? In your MIG measurement where your slot or slit was outside the luminous zone, would variations of the luminosity, here, change the quantitative measurement you would get?

Dr. Grove: It does, yes. Yes, actually, from the spectrographic standpoint, spectrographic theory, when you have oxygen in the system, you are seeing excited oxygen. That's what gives you your lines. Now, it does not make any difference whether you are exciting that oxygen, if you have enough heat to do it; whether you're looking at it through the arc; or whether you're looking at the side of the arc. However, the imaging of our slit on the side of the arc, we find, is very difficult to reproduce. In other words, we were lucky the first time we tried this. We got a position, I guess, apparently good because we got nice sensitivity, and got rather nice data. That report looked nice, coming down here to NASA. I hate to tell you what the next one looked like, after we set it up again. And it simply meant that after we tried setting it up two or three times with hand equipment that we couldn't precisely reset, we could not reproduce this close enough. But if you're looking through the arc at it, you're actually looking at the arc gases in the periphery here, plus you're getting some in depth. It does not make any difference if you're off a quarter-inch one side or the other here. You're still getting enough excitation.

Mr. Jackson: Another one, back here; yes, please?

Mr. Berge: Have you been able to relate these contaminants to particular weld defects? Will something practical come of this?

Dr. Grove: We hope to. If we don't show something in the next two or three years, there are going to be some other people awfully unhappy with us. There have been some studies done along this line, I think it's in the British Welding Journal of about four or five years ago. They were not using this particular technique for monitoring. If we are seeing, notice I'm saying "if we are seeing", what is in the metal itself, there should be a relationship. If the metal is absorbing the gas that's coming around the shield--we know we're seeing that there should be a relationship. I think we will.

Mr. Jackson: I think that is all we will have time for. I certainly want to thank you, Doctor, and one thing we are sure about---when we get a new tool into a new field and get to working with it, the first thing you know we are going to have new information that will help the practical man and boy, like you and me, in order to do the job of welding. Thank you.

EVALUATION OF THE COMBINED EFFECTS OF POROSITY AND  
MISMATCH ON THE WELD STRENGTHS OF 6061-T6 AND 2014-T6  
(AS-WELDED) ALUMINUM ALLOYS

By

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## ABSTRACT

The combined effects of mismatch and porosity on the "As-Welded" strength of 2014-T6 aluminum alloy and on the strength of 6061-T6 aluminum alloy, heat treated after welding, were determined and a discussion of the test results is contained herein. This investigation was authorized by the Gemini program.

## INTRODUCTION

The individual effects of mismatch and porosity in aluminum alloy weldments have previously been determined by the Martin Company and several other companies in the missile industry. As a result of those investigations, weld strength allowables were calculated based on the assumption that the effects of porosity and mismatch on weld strength are additive. The validity of this assumption was questioned, as it imposed severe limitations on allowable mismatch and porosity. For example: a repair weld to a 2014-T6 "As-Welded" detail that contained a  $P_2$  level of porosity could not tolerate any mismatch in the joint area if the 25,000-psi strength level allowable was to be maintained.

The subject program was conducted by Advanced Manufacturing Technology Laboratory and Materials Engineering of Martin-Baltimore to determine the effects of combined mismatch and porosity on weldment strengths of 2014-T6 and 6061-T6 aluminum alloys. The effort was expanded to include two thicknesses of 2014-T6 (0.190 and 0.090 inch) in the "As-Welded" condition, 6061-T6 heat treated after welding in three thicknesses (0.070, 0.100 and 0.125 inch), and to establish weld strength allowables for these alloys and conditions.

## PROCEDURE AND RESULTS

The combined effects of mismatch and porosity were established for 2014-T6 aluminum alloy (0.090 and 0.190 inch) in the "As-Welded" condition and 6061-T6 aluminum alloy (0.070, 0.100 and 0.125 inch) in the heat treated condition after welding. Welding was performed in accordance with Martin Process Specification EPS-55013 for 6061-T6 aluminum alloy and PB-55406 for the 2014-T6 aluminum alloy. Welds were accomplished by the tungsten inert gas (TIG) automatic welding process utilizing a 300-amp power source to provide d-c straight polarity welding current. The welding gas was helium and the filler was 4043 aluminum in accordance with Federal Specification QQ-R-566. The welding jig consisted of a grooved steel backup and aluminum hold-down bars placed on either side of the weld.

Radiographic inspection was utilized to select specimens for tensile testing at seven varying porosity levels (Figure 10). Porosity levels from  $P_0$  to  $P_6$ , inclusive, were selected by comparison with the Standards of Gemini Document, "Design Criteria--Welding," Radiographic Standards for scattered porosity. To achieve the various porosity levels, helium gas with varied dew point was utilized. This, initially, proved to be the most difficult part of the task. Preliminary investigations were accomplished on the 0.190 inch 2014-T6 aluminum welds utilizing various hydrocarbons to form the gas porosity. The most successful proved to be the standard red grease marking pencil. However, this method of obtaining porosity was not completely satisfactory due to inclusions

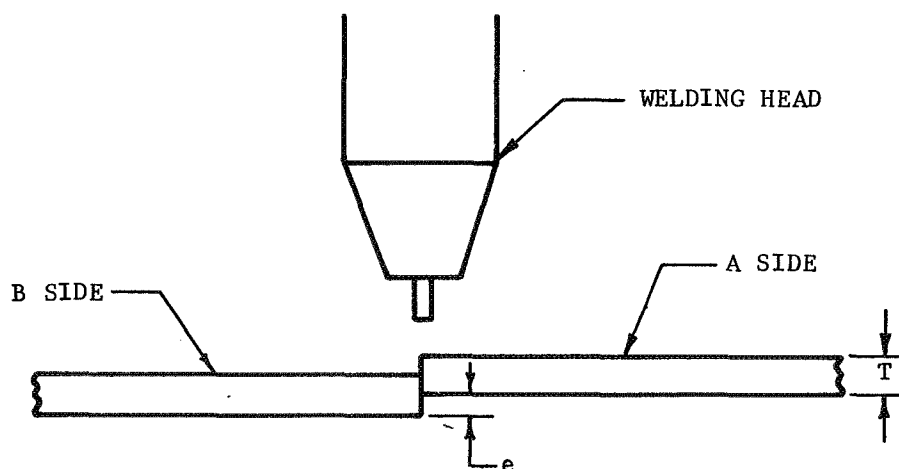
or cross-type oxides that occasionally formed. Further development evolved the highly successful technique of adding water vapor to the inert shielding gas. The chief source of porosity is believed to be hydrogen gas that dissolves in the molten weld metal. Water vapor is dissociated in the welding arc providing atomic hydrogen for dissolution in the molten metal.

Mismatch in the welded specimens was obtained by shimming one sheet to the desired offset level in the welding jig before the weld was accomplished. Mismatch levels of 0, 15, 30, 50 and 70 percent were tested in conjunction with the seven porosity levels,  $P_0$  through  $P_6$ . Each set of test specimens consisted of approximately 10 to 20 specimens having identical levels of porosity and mismatch. All specimens were tension tested to failure in Baldwin PTE Universal testing machines of 5000-lb capacity utilizing Tenclin grips to hold and align them during test. Tensile strength was calculated on the basis of average parent material cross-sectional area adjacent to the weld. The weld bead reinforcement was not removed before testing.

The welding parameters (amperage-voltage, etc.), established for each type of material and thickness, remained essentially constant throughout the test program. Heat input, for all practical purposes, remained unchanged, thus assuring that actual weld strength degradation would be a function of porosity and mismatch and not a function of varying heat input.

As shown in Figure 1, the panels to be joined were marked A and B. The panel closest to the welding torch was identified as A. Origin of failure, during testing, was noted in relation to A or B side.

Heat treatment of the 6061-T6 specimens was in accordance with Martin Process Specification EPS-10310: free-fall quenched to minimize distortion.



$$\text{MISMATCH (\%)} = (e/T) 100$$

Figure 1. Schematic Showing Torch Position in Relation to Sheet Material Nomenclature

Tension test results for 0.090-inch 2014-T6 as-welded are listed in Table I, and the average strengths for specimens at various mismatch and porosity levels are shown graphically in Figure 2. Preliminary statistical summaries are given in Table II. The coefficient of variation,  $C_v$  ( $C_v = \frac{100\sigma}{\bar{X}}$ ), has been established for each group of specimens according to the method described by Haire and Gorrell (Reference 5). This method utilizes the minimum test value ( $X_L$ ) and the mean test value ( $\bar{X}$ ) to estimate the coefficient of variation. The chief advantages of the method are the ease of calculation and the ability to make reasonable estimates from skewed data which are often obtained in weld tensile tests. Minimum weld strength estimates at the 99 percent confidence level ( $2.33\sigma$  below  $\bar{X}$ ) were made for each set of weld samples. The minimum strength value at 99 percent confidence level ( $W_{99}$ ) is estimated as follows:

$$W_{99} = \bar{X} - 2.33\sigma = \bar{X} - \left( 2.33\bar{X} \cdot \frac{C_v}{100} \right)$$

where

$\bar{X}$  = average (mean) value

$\sigma$  = standard deviation for series

$C_v$  = coefficient of variation

$$\sigma = \frac{\bar{X} \cdot C_v}{100}$$

The data generated for the 0.190 inch thick 2014-T6 in the "As-Welded" condition is summarized in Table III and graphically illustrated in Figure 3. The test data in this portion of the program is presented in tabular form in Appendix A. A plot of the relationship of the data at the 99 percent confidence level as determined by the statistical method (1) is shown in Table IV.

Tension test results for 0.070-inch thick 6061-T6 are listed in Table V and the preliminary statistical summary for 0.070-inch thick 6061-T6 is given in Table VI. The tension test results for 0.100-inch thickness specimens of 6061-T6 are listed in Table VII and the results of 0.125-inch thick 6061-T6 material are given in Table VIII. The statistical summaries for the two thicknesses are given in Table IX (0.100-inch material) and Table X (0.125-inch material). Graphic illustrations on the 6061-T6 heat treated specimens are shown in Figures 4, 5, 6, 7, 8 and 9.

A more exhaustive statistical study of weld mismatch and porosity tensile data is now being carried out by Mr. E. Haire and associates for the Gemini Program.

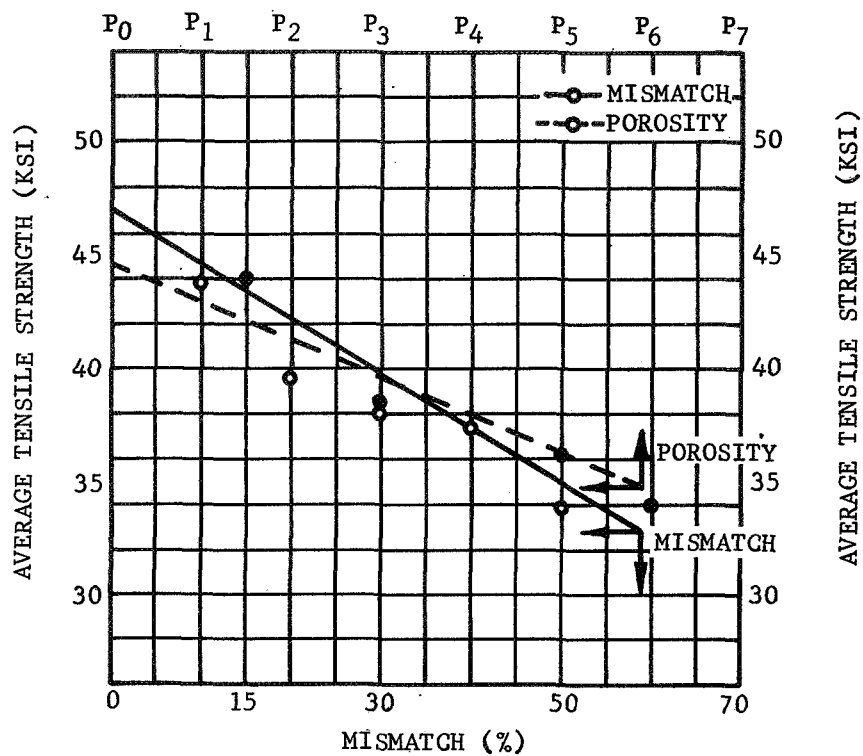


Figure 2. Effect of Mismatch and Porosity Upon Weld Tensile Strength on 0.090 Thick 2014-T6 As-Welded

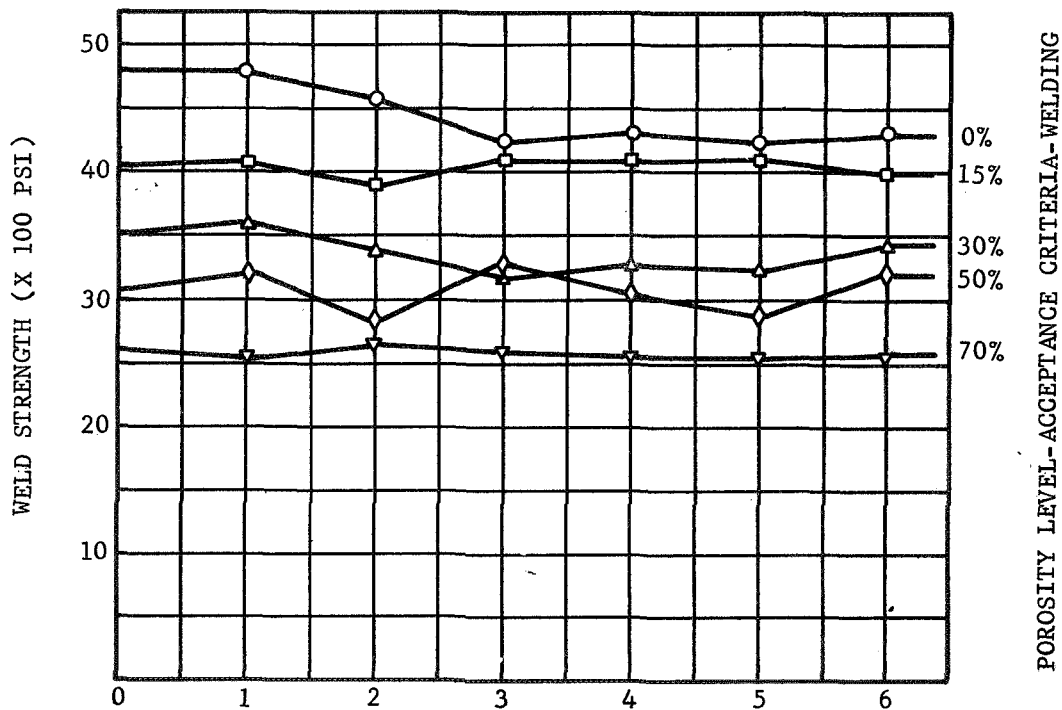


Figure 3. Average Weld Strength as Affected by the Combination of Mismatch and Porosity on 0.190 Thick 2014-T6. As-Welded

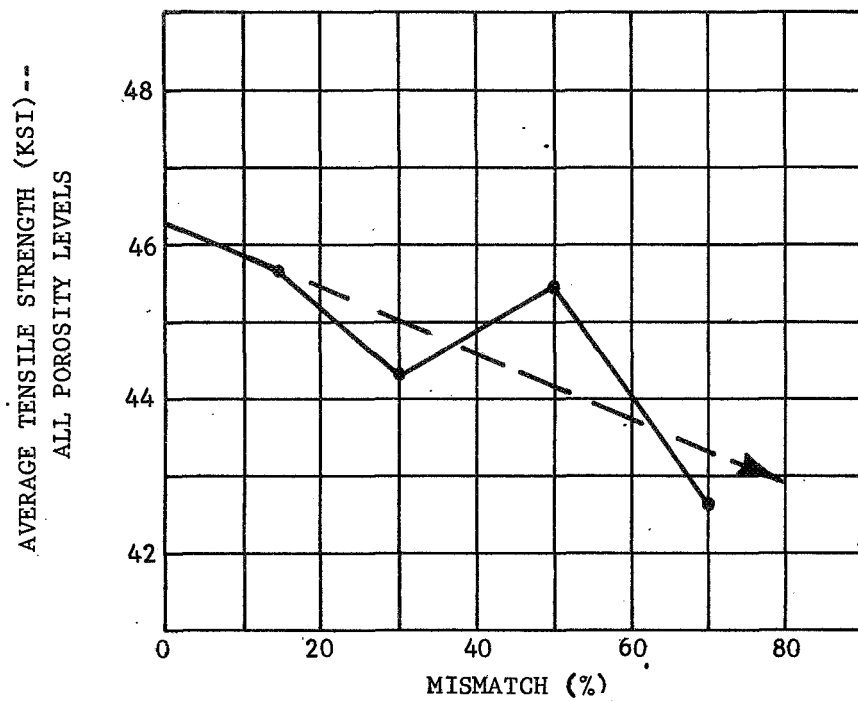


Figure 4. Effect of Mismatch (0.070 in.)

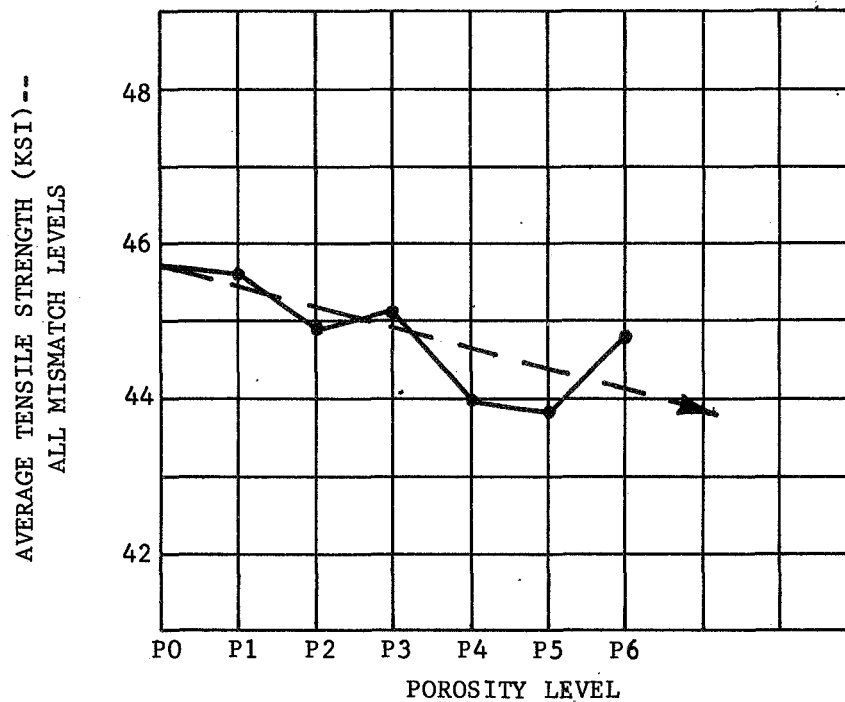


Figure 5. Effect of Porosity Level



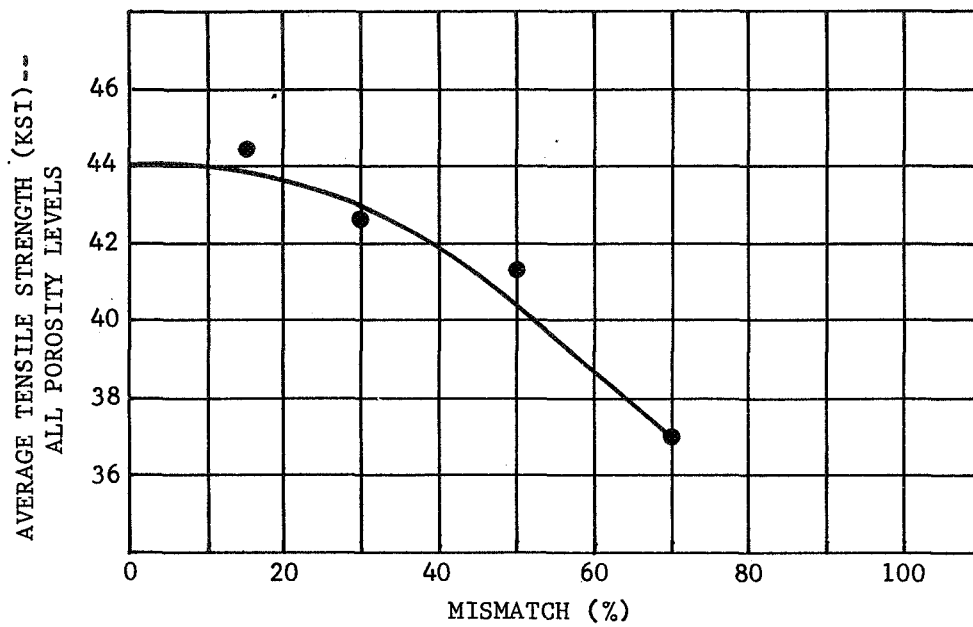


Figure 6. Effect of Mismatch (0.100 in.)

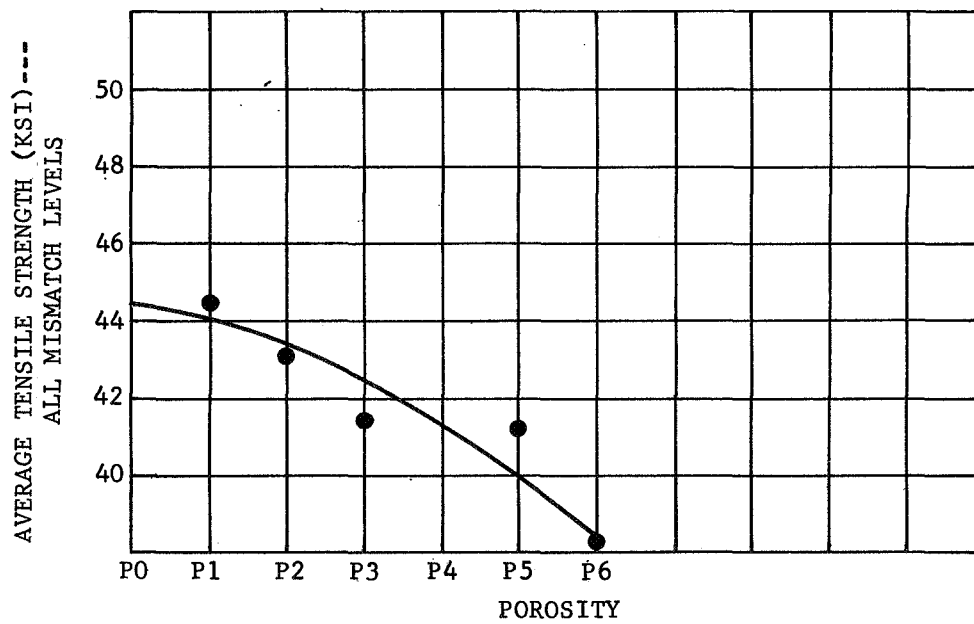


Figure 7. Effect of Porosity (0.100 in.)

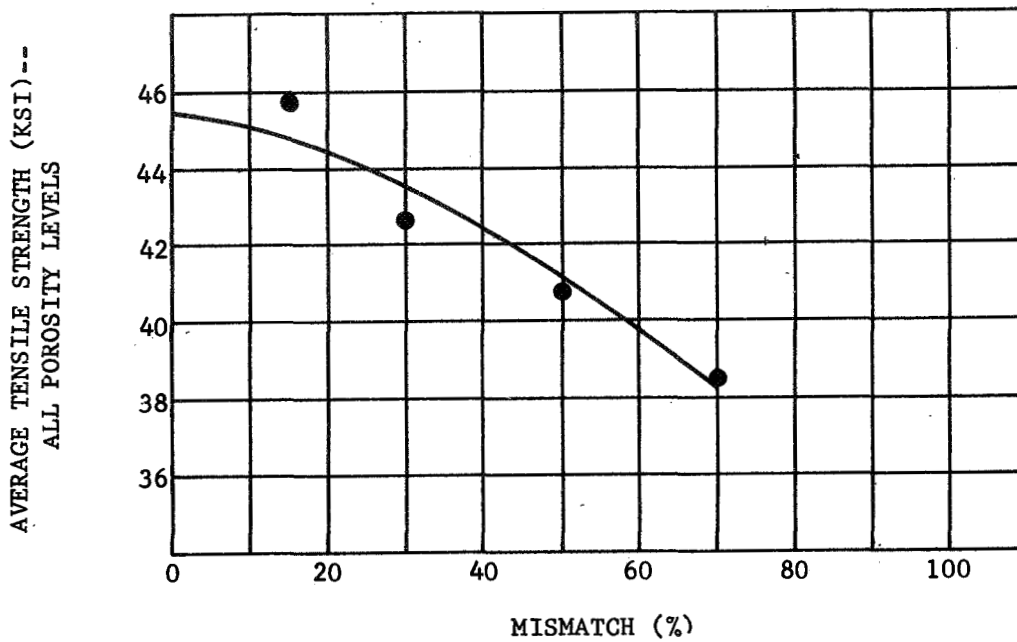


Figure 8. Effect of Mismatch (0.125 in.)

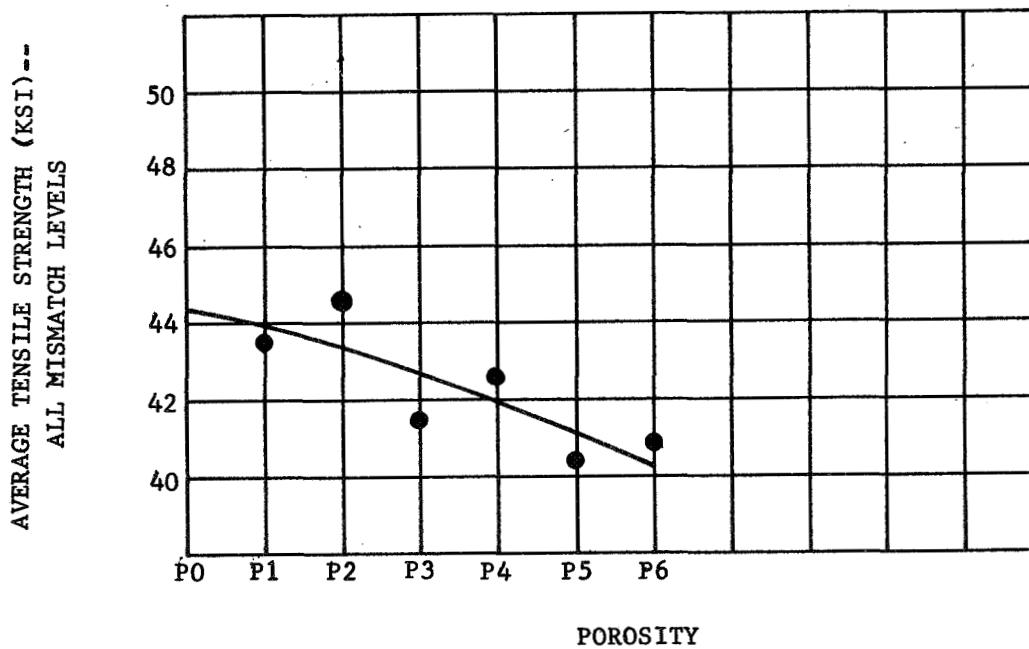


Figure 9. Effect of Porosity (0.125 in.)

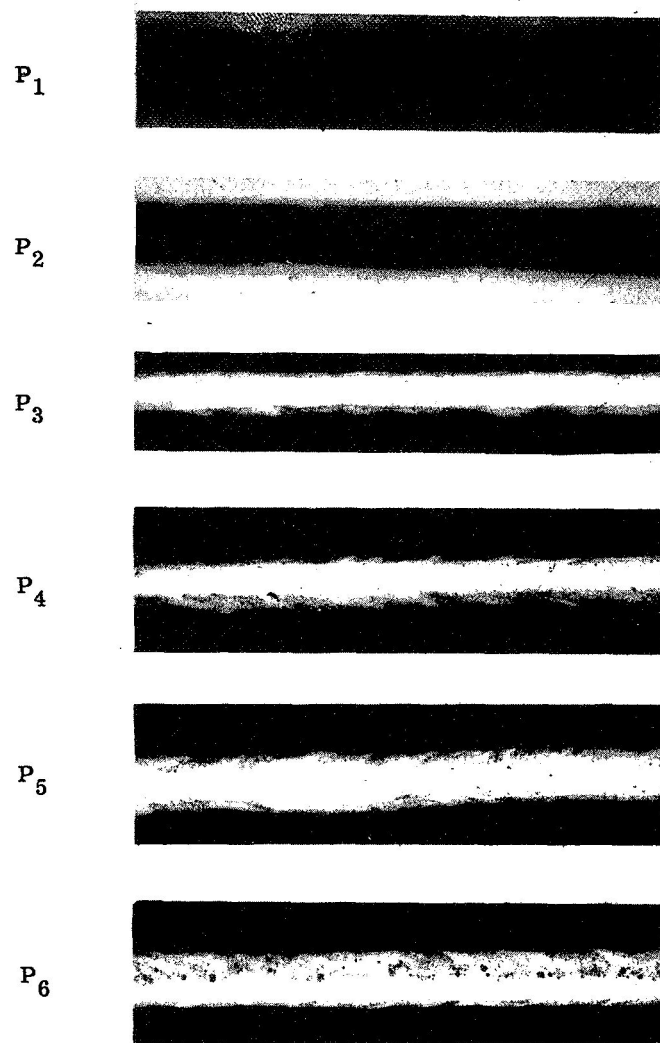


Figure . 10. Radiographic Standards for Scattered Porosity, Grades A and B

## CONCLUSION

The combined effects of mismatch and porosity on the strengths of "As-Welded" 2014-T6 aluminum alloy and 6061-T6 aluminum alloy, heat treated after welding, were determined.

In the 2014-T6 "as-welded" condition it was concluded that both mismatch and porosity are factors that contribute to the lowering of strength as the level of each increases in magnitude. Mismatch is somewhat the greater of the two factors. Porosity appears to be a more significant factor in the thinner (0.090 inch) material than it is in the (0.190 inch) material.

In the 6061-T6 aluminum alloy, heat treated after welding, it was concluded that both mismatch and porosity are factors that contribute to the lowering of strength as the level of each increases in magnitude.

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3. "Evaluation of the Combined Effects of Porosity and Mismatch on Weld Strength--6061 (0.070 in. thick) Aluminum Alloy Heat Treated After Welding," Materials Engineering Memorandum Report No. 8-64, Addendum No. 1, dated 10 April 1964.
4. "Evaluation of the Combined Effects of Porosity and Mismatch on Weld Strength-2014-T6 Aluminum Alloy 0.090 in. thick 'As-Welded.'" Martin-Baltimore Materials Engineering Memorandum Report No. 37-64, dated 8 June 1964.
5. "Structures Reliability Report Volume I--Methods and Data Design Manual," E. T. Haire and W. Gorrell, Martin-Baltimore ER 11862, December 1961.

Table I. Tensile Test Data for 0.090-inch 2014-T6  
(Tensile Strength, ksi),

Specification No.	<u>0% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	55.9	54.2	53.7	47.9	43.0	40.0	37.0
2	55.3	52.9	48.5	47.6	44.3	38.7	39.2
3	52.9	54.3	53.2	48.1	41.4	41.2	37.8
4	55.2	54.9	50.9	45.7	44.5	40.1	42.1
5	55.8	56.3	49.5	45.1	43.4	39.8	44.9
6	56.1	55.1	44.8	45.6	43.0	42.0	39.3
7	52.3	54.1	53.1	44.4	42.8	41.9	43.0
8	55.9	54.6	53.4	46.7	41.7	39.2	42.8
9	55.9	53.4	41.0	46.8	44.8	42.1	34.6
10	52.3	54.4	52.9	47.0	43.5	41.8	44.3
High	56.1	56.3	53.7	48.1	44.8	42.1	44.9
Low	52.3	52.9	41.0	44.4	41.4	38.7	34.6
Average	54.8	54.4	50.1	46.5	43.2	40.7	40.5
<u>15% Mismatch</u>							
1	52.8	53.2	40.3	43.0	42.8	41.7	34.2
2	55.5	54.4	42.5	42.6	44.2	42.3	33.4
3	55.5	52.8	39.5	42.8	42.9	42.2	33.5
4	53.9	50.4	39.1	42.5	42.6	42.0	33.6
5	56.4	51.9	39.6	44.0	43.2	40.8	33.2
6	53.3	52.0	38.7	41.8	42.6	43.6	33.1
7	50.9	53.6	38.7	42.1	41.1	43.2	33.3
8	56.1	53.3	39.0	42.8	41.7	41.5	34.2
9	54.4	54.3	39.4	41.4	42.7	39.9	33.6
10	56.4	52.0	39.6	43.7	41.7	43.3	31.4
High	56.4	54.4	42.5	44.0	44.2	43.6	34.2
Low	50.9	50.4	38.7	41.4	41.1	39.9	31.4
Average	54.5	52.8	39.6	42.7	42.6	42.1	33.4
<u>30% Mismatch</u>							
1	42.9	41.0	37.5	38.6	34.4	34.2	32.2
2	37.5	46.2	40.5	39.9	36.7	40.8	33.8
3	44.3	45.4	38.0	37.9	32.2	33.8	34.2
4	40.0	39.6	39.1	36.2	40.4	32.4	32.7
5	39.5	41.5	40.1	37.9	35.4	35.3	30.3
6	40.3	39.8	38.0	37.3	42.0	32.8	29.8

Table I (continued)

<u>30% Mismatch</u>							
<u>Specification No.</u>	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
7	43.7	45.7	34.7	36.3	41.1	39.4	38.0
8	44.5	47.0	39.0	39.8	40.7	34.4	41.0
9	44.0	40.8	39.6	40.0	36.2	33.9	31.4
10	42.2	36.6	38.4	37.8	38.6	32.8	33.3
High	44.5	47.0	40.5	40.0	42.0	40.8	41.0
Low	37.5	36.6	34.7	36.2	32.2	32.4	29.8
Average	41.9	42.4	38.5	38.2	37.8	35.0	33.7
<u>50% Mismatch</u>							
1	37.2	37.3	40.9	32.3	29.9	30.4	33.3
2	38.3	35.6	42.8	28.1	32.1	29.0	35.4
3	37.8	35.3	38.5	29.8	34.2	33.6	29.1
4	37.0	35.7	39.7	29.5	33.0	28.5	29.9
5	37.7	36.8	39.4	30.5	30.9	30.7	26.3
6	38.2	34.8	39.8	31.3	34.4	30.7	28.3
7	38.4	35.9	41.2	31.2	33.6	29.3	28.2
8	36.1	34.7	39.5	30.6	33.5	34.7	33.9
9	36.0	37.4	40.6	31.5	32.1	28.3	32.5
10	33.4	31.9	44.0	29.8	32.3	29.2	32.5
High	38.4	37.4	44.0	32.3	34.4	34.7	35.4
Low	33.4	31.9	38.5	28.1	29.9	28.3	26.3
Average	37.0	35.5	40.6	30.5	32.6	30.4	30.9
<u>70% Mismatch</u>							
1	37.6	30.9	28.9	36.9	35.9	34.7	32.4
2	37.5	20.2	26.1	37.3	31.5	34.9	28.3
3	30.3	30.9	28.9	32.3	35.4	31.8	35.1
4	36.2	30.1	29.4	31.6	36.9	33.4	31.3
5	33.1	31.6	30.9	36.6	32.2	25.2	33.5
6	37.3	27.0	31.4	33.5	29.9	31.8	29.2
7	36.5	30.1	28.4	35.6	28.1	34.4	31.9
8	32.9	28.9	29.0	35.2	26.7	30.4	30.0
9	37.7	30.1	29.8	33.5	26.4	36.0	31.1
10	35.9	29.1	30.7	34.0	28.3	34.7	--
High	37.7	31.6	31.4	37.3	36.9	36.0	35.1
Low	30.3	20.2	26.1	31.6	26.4	25.2	28.3
Average	35.5	28.9	29.4	34.6	31.1	32.7	31.4

Table II. Statistical Analysis of 0.090-inch 2014-T6  
Weld Tensile Data.

Mismatch (%)		<u>P</u> <u>0</u>	<u>P</u> <u>1</u>	<u>P</u> <u>2</u>	<u>P</u> <u>3</u>	<u>P</u> <u>4</u>	<u>P</u> <u>5</u>	<u>P</u> <u>6</u>
0	N	10	10	10	10	10	10	10
	$X_L$	52,300	52,900	41,000	44,400	41,400	38,700	34,600
	$\bar{X}$	54,800	54,400	50,100	46,500	43,200	40,700	40,500
	$C_v$	3.2	2.2	12.8	3.2	2.9	3.6	10.4
	$W_{99}$	50,700	51,600	35,200	43,000	40,300	37,300	30,700
15	N	10	10	10	10	10	10	10
	$X_L$	50,900	50,400	38,700	41,400	41,100	39,900	31,400
	$\bar{X}$	54,500	52,800	39,600	42,700	42,600	42,100	33,400
	$C_v$	5.0	3.2	1.4	2.2	2.5	3.7	4.0
	$W_{99}$	48,500	48,800	38,300	40,500	40,100	38,500	30,300
30	N	10	10	10	10	10	10	10
	$X_L$	37,500	36,000	34,700	36,200	32,200	32,400	29,800
	$\bar{X}$	41,900	42,400	38,500	38,200	37,800	35,000	33,700
	$C_v$	7.5	9.8	7.0	3.6	10.4	5.2	8.4
	$W_{99}$	34,600	32,700	32,200	35,000	28,700	30,800	27,100
50	N	10	10	10	10	10	10	10
	$X_L$	33,400	31,900	38,500	28,100	29,900	28,300	26,300
	$\bar{X}$	37,000	35,500	40,600	30,500	32,600	30,400	30,900
	$C_v$	6.8	7.2	3.6	5.7	5.9	6.0	11.6
	$W_{99}$	31,100	29,500	37,200	26,500	28,100	26,100	22,500
70	N	10	10	10	10	10	10	9
	$X_L$	30,300	20,200	26,100	31,600	26,400	25,200	28,300
	$\bar{X}$	35,500	28,900	29,400	34,600	31,100	32,700	31,400
	$C_v$	10.4	21.4	7.9	6.3	10.7	14.8	7.4
	$W_{99}$	26,900	14,500	24,000	29,500	2,300	21,400	26,000

NOTES:

N = number of tests

$X_L$  = minimum value

$\bar{X}$  = average (mean) value

$C_v$  = coefficient of variation in %

$W_{99}$  = minimum value estimate at 99% probability level

Table III, Weld Strength Data on the Combined Effects of Mismatch and Porosity of 0.190-inch 2014-T6 As-Welded,

Mismatch (%)	P <sub>0</sub>	P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>	
0	45,000	43,100	40,600	36,700	39,800	38,700	39,400	L
	48,100	47,800	45,700	42,300	43,400	42,300	43,100	AV
	51,400	51,200	48,700	46,500	48,100	48,600	45,500	H
15	34,500	34,700	30,100	33,000	35,000	34,000	36,800	L
	40,600	40,900	39,000	41,000	40,900	41,100	39,800	AV
	47,300	47,400	47,900	47,400	46,400	46,500	46,500	H
30	33,200	31,400	28,000	27,900	29,900	28,100	30,200	L
	35,200	36,100	33,900	31,800	32,600	32,300	34,300	AV
	37,200	41,900	36,800	36,000	35,700	36,300	40,100	H
50	28,000	32,200	25,200	28,400	22,500	24,600	29,400	L
	30,900	32,300	28,500	32,700	30,500	28,900	32,000	AV
	33,200	34,700	32,400	37,700	33,800	35,500	38,400	H
70	24,400	22,000	24,000	23,900	22,300	22,000	23,000	L
	26,400	25,400	26,500	26,000	25,600	25,500	25,700	AV
	30,000	30,400	32,400	28,600	30,500	28,100	29,300	H



Table IV. Statistical Summary of Weld Strength Data  
of 0.190 inch 2014-T6 As-Welded.

Mismatch (%)		P <sub>0</sub>	P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>
	N	21	20	21	20	20	20	20
	W <sub>s1</sub>	45,000	43,100	40,600	36,700	39,800	38,700	39,400
0	$\bar{W}_s$	48,100	47,800	45,700	42,300	43,400	42,300	43,100
	C <sub>vs</sub>	3.6	5.6	6.4	7.3	4.5	5.0	5.0
	W <sub>99</sub>	44,100	41,600	38,900	35,100	38,900	37,400	38,200
	N	22	21	21	20	20	20	20
	W <sub>s1</sub>	34,500	34,700	30,100	33,000	35,000	34,000	36,800
15	$\bar{W}_s$	40,600	40,900	39,000	41,000	40,900	41,100	39,800
	C <sub>vs</sub>	8.5	8.5	13.0	11.5	8.0	9.8	4.5
	W <sub>99</sub>	32,600	32,800	27,100	30,100	33,200	31,800	35,600
	N	21	20	22	20	16	12	19
	W <sub>s1</sub>	33,200	31,400	28,000	27,900	29,900	28,100	30,00
30	$\bar{W}_s$	35,800	36,100	33,900	31,800	32,600	32,300	34,300
	C <sub>vs</sub>	3.8	7.3	9.8	6.8	4.8	8.5	6.8
	W <sub>99</sub>	32,600	30,100	24,200	26,700	28,900	26,000	29,000
	N	21	20	20	20	20	17	14
	W <sub>s1</sub>	28,000	30,200	25,200	28,400	22,500	24,600	25,600
50	$\bar{W}_s$	30,900	32,300	28,500	32,700	30,500	28,000	32,000
	C <sub>vs</sub>	5.0	3.8	6.8	7.3	14.6	7.6	12.8
	W <sub>99</sub>	27,300	29,500	24,100	27,100	20,300	23,800	22,500
	N	22	20	15	18	20	18	20
	W <sub>s1</sub>	24,400	22,000	24,000	23,900	22,300	22,000	23,000
70	$\bar{W}_s$	26,400	25,400	26,500	26,000	25,600	25,500	25,700
	C <sub>vs</sub>	4.5	7.3	5.6	4.7	7.3	8.2	6.4
	W <sub>99</sub>	23,600	21,200	23,000	23,200	21,200	20,600	22,000

NOTES : N = number of tests  
W<sub>s1</sub> = lowest strength value  
 $\bar{W}_s$  = average (mean) strength value  
C<sub>vs</sub> = coefficient of variation, %  
W<sub>99</sub> = minimum weld strength at 99% confidence level  
 $W_{99} = \bar{W}_s - (\bar{W}_s \cdot C_{vs} \cdot 2.33)$

Table V. Tensile Data for 0.070-inch 6061-T6 Welds (ksi).

<u>0% Mismatch</u>							
<u>Specification No</u>	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	46.2	46.5	47.9	46.9	47.0	44.4	45.8
2	47.6	46.1	46.3	47.8	44.4	43.2	44.6
3	48.4	47.2	47.1	47.2	47.0	44.2	46.8
4	47.4	45.2	47.4	47.7	47.5	43.9	44.9
5	46.8	47.2	47.0	47.0	46.2	43.9	44.5
6	46.8	46.4	46.5	46.6	47.4	43.8	46.5
7	47.5	48.1	47.4	46.4	42.5	41.5	46.5
8	46.5	47.3	46.7	46.3	45.9	44.7	43.6
9	47.2	47.8	47.3	47.4	47.9	43.9	46.0
10	46.7	47.2	47.1	46.3	46.1	44.1	46.3
High	48.4	48.1	47.9	47.8	47.9	44.7	46.8
Low	46.2	45.2	46.3	46.3	42.5	41.5	43.6
Average	47.11	46.90	47.07	46.96	46.19	43.76	45.55
<u>15% Mismatch</u>							
1	46.0	47.3	44.8	44.4	46.4	44.7	44.9
2	46.3	46.5	45.1	45.0	45.9	43.9	45.0
3	46.3	46.4	44.3	45.0	46.1	42.5	44.9
4	46.8	47.1	45.0	45.8	46.4	45.1	46.6
5	46.8	46.2	45.0	45.6	46.4	41.0	44.4
6	46.5	46.5	44.8	44.9	46.6	45.0	44.6
7	46.3	46.6	44.3	45.2	46.3	43.6	44.5
8	46.4	47.1	44.8	45.1	46.2	44.7	46.4
9	46.9	46.7	45.1	45.6	46.5	44.8	47.1
10	45.5	46.4		47.1	46.7	44.7	45.6
High	46.9	47.3	45.1	47.1	46.7	45.1	47.1
Low	45.5	46.2	44.3	44.4	45.9	41.9	44.4
Average	46.38	46.68	44.80	45.37	46.35	44.09	45.40
<u>30% Mismatch</u>							
1	44.8	45.4	45.5	45.2	40.2	43.3	43.3
2	44.6	45.4	44.9	44.7	39.4	44.8	44.6
3	44.6	45.2	45.2	46.7	46.0	43.6	44.2
4	45.0	44.6	44.9	45.5	38.5	45.0	44.4
5	44.5	44.8	44.8	44.8	41.6	43.9	45.1
6	44.1	44.9	44.8	43.5	46.6	44.9	44.0
7	45.0	45.0	45.1	46.5	45.2	42.8	46.1

Table V (continued)

Specification No.	<u>30% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
8	44.9	44.7	45.0	45.0	35.6	44.9	42.6
9	45.3	45.1		43.6	47.2	45.0	45.0
10	44.9	44.8		42.2	38.2	43.0	44.8
High	45.3	45.4	45.5	46.7	47.2	45.0	46.1
Low	44.1	44.6	44.8	42.2	35.6	42.8	42.6
Average	44.77	44.99	45.02	44.77	41.85	44.12	44.41
	<u>50% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	47.0	46.0	44.9	45.8	40.5	47.4	43.6
2	46.8	46.3	44.8	43.2	42.4	46.1	44.4
3	46.9	46.6	45.0	45.6	44.8	46.4	46.7
4	46.3	46.3	44.7	45.8	43.5	45.8	47.5
5	46.6	46.6	44.8	45.2	44.5	46.6	44.7
6	46.5	46.8	44.6	45.4	45.2	46.2	45.1
7	46.4	45.9	44.7	45.5	40.7	47.3	45.3
8	46.5	46.8	44.4	45.4	43.3	45.8	46.5
9	46.7	46.4	44.6	45.3	43.2	45.2	44.1
10	46.9	46.4		45.6	41.9	46.6	47.2
High	47.0	46.8	45.0	45.8	45.2	47.4	47.5
Low	46.3	45.9	44.4	43.2	40.7	45.2	43.6
Average	46.66	46.61	44.72	45.28	43.20	46.34	45.51
	<u>70% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	44.6	42.9	42.7	43.0	44.8	45.5	45.5
2	43.4	42.7	42.4	43.6	35.2	44.2	45.1
3	43.7	43.6	43.2	42.5	33.9	45.6	45.3
4	43.4	40.7	41.9	43.4	46.9	34.1	46.0
5	43.5	44.9	42.9	42.9	37.5	32.1	45.7
6	43.2	45.2	43.3	43.3	44.7	32.5	44.4
7	43.5	42.2	42.9	42.8	45.0	35.7	45.7
8	43.3	41.5	42.6	43.5	36.7	45.6	47.2
9	42.7	43.9	42.5	43.2	45.8	45.5	33.5
10	43.4	42.4	42.3		47.0	45.6	33.2
High	44.6	45.2	43.3	43.6	47.0	45.6	47.2
Low	42.7	40.7	41.9	42.5	33.9	32.1	33.2
Average	43.47	43.00	42.67	43.13	41.75	40.64	43.16

Table VI. Statistical Analysis of 0.070-inch Weld Tensile Data.

Mismatch (%)		P <sub>0</sub>	P <sub>1</sub>	P <sub>2</sub>	P <sub>3</sub>	P <sub>4</sub>	P <sub>5</sub>	P <sub>6</sub>
0	N	10	10	10	10	10	10	10
	X <sub>L</sub>	46,200	45,200	46,300	46,300	42,500	41,500	43,600
	$\bar{X}$	47,110	46,900	47,070	46,960	46,190	43,760	45,550
	C <sub>v</sub>	1.4	2.6	1.2	1.2	5.7	3.6	3.2
	W <sub>99</sub>	45,570	44,060	45,750	45,650	40,060	40,090	42,150
15	N	10	10	9	10	10	10	10
	X <sub>L</sub>	45,500	46,200	44,300	44,400	45,900	41,900	44,400
	$\bar{X}$	46,380	46,680	44,800	45,370	46,350	44,090	45,400
	C <sub>v</sub>	1.4	0.9	0.6	1.5	0.7	3.6	1.4
	W <sub>99</sub>	44,870	45,700	44,170	43,790	45,590	40,390	43,920
30	N	10	10	8	10	10	10	10
	X <sub>L</sub>	44,100	44,600	44,800	42,200	35,600	42,800	42,600
	$\bar{X}$	44,770	44,990	45,020	44,770	41,850	44,120	44,410
	C <sub>v</sub>	0.7	0.5	0.4	3.9	10.7	2.2	2.9
	W <sub>99</sub>	44,040	44,460	44,600	40,700	31,450	41,860	41,410
50	N	10	10	9	10	10	10	10
	X <sub>L</sub>	46,300	45,900	44,400	43,200	40,700	45,200	43,600
	$\bar{X}$	46,660	46,410	44,720	45,280	43,200	46,340	45,510
	C <sub>v</sub>	1.0	0.7	0.6	3.3	4.2	1.4	2.9
	W <sub>99</sub>	45,570	45,650	44,090	41,800	38,970	44,830	42,430
70	N	10	10	10	9	10	10	10
	X <sub>L</sub>	42,700	40,700	41,900	42,500	33,900	32,100	33,200
	$\bar{X}$	43,470	43,000	42,670	43,130	41,750	40,640	43,160
	C <sub>v</sub>	1.1	3.7	1.3	1.0	13.5	15.0	16.4
	W <sub>99</sub>	42,350	39,290	41,380	42,120	28,600	26,440	26,560

NOTES : N = number of specimens in series  
X<sub>L</sub> = low value of the series  
 $\bar{X}$  = average (mean) value  
C<sub>v</sub> = coefficient of variation, %  
W<sub>99</sub> = minimum weld tensile strength value at 99% probability level

Table VII. 6061-T6 Weld Strength Data--0.100 inch (1).

Specification No.	<u>0% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	45,000	45,000	42,800	45,500	43,000	43,500	43,600
2	45,200	45,100	44,400	43,900	42,900	44,300	44,600
3	45,200	45,800	45,100	44,100	43,700	45,000	42,600
4	45,200	45,400	45,200	43,900	41,100	42,700	39,700
5	45,600	45,300	45,300	43,200	44,000	43,100	42,300
6	45,300	45,100	44,600	45,400	43,300	43,900	39,900
7	45,500	45,200	45,000	45,300	44,700	42,500	39,200
8	45,000	45,300	45,500	45,600	45,500	45,300	43,000
9	45,300	45,200	45,200	44,000	44,300	42,600	44,300
10	45,200	45,200	45,200	43,500	44,200	44,000	36,200
High	45,600	45,800	45,500	45,600	45,500	45,300	44,600
Low	45,000	45,000	42,800	43,200	41,100	42,500	36,200
Average	45,260	45,260	44,840	44,440	43,690	43,690	41,540

(1) Tensile strength in pounds per square inch.

<u>15% Mismatch</u>							
1	45,400	45,000	45,400	44,700	42,300	45,100	43,600
2	45,100	45,400	44,400	45,000	42,400	43,500	43,500
3	45,100	45,200	45,200	45,300	43,400	43,300	43,600
4	46,000	45,000	44,200	44,900	44,700	43,200	43,100
5	45,400	45,200	44,500	44,800	44,700	45,600	44,100
6	44,600	45,100	43,500	43,000	43,800	42,700	45,300
7	45,300	45,100	44,100	45,000	43,000	43,900	42,400
8	45,200	45,400	45,200	43,700	44,200	45,200	45,500
9	45,300	45,300	43,800	45,200	43,700	45,000	45,400
10	45,300	45,400	45,400	44,700	42,700	45,000	45,500
High	46,000	45,400	45,500	45,300	44,700	45,600	45,500
Low	44,600	45,000	43,500	43,000	42,300	42,700	42,400
Average	45,270	45,210	44,580	44,630	43,490	44,250	44,210

<u>30% Mismatch</u>							
1	45,400	45,100	45,300	42,400	42,100	40,600	36,500
2	45,500	45,600	45,000	43,100	43,900	40,400	32,600
3	45,700	45,300	45,300	42,400	40,200	42,800	34,300
4	45,500	45,200	45,200	41,300	43,700	43,000	35,400
5	45,200	45,300	45,000	41,700	41,400	41,200	33,200
6	45,200	45,500	45,300	42,200	41,500	43,300	34,300
7	45,000	45,300	44,800	45,300	42,300	42,800	38,400
8	45,000	45,700	45,100	42,600	41,500	42,200	38,400
9	45,100	45,300	45,200	45,300	42,900	40,800	35,300
10	45,200	45,400	45,000	42,000	41,800	43,500	38,600
High	45,700	45,700	45,300	45,300	43,900	43,500	38,600
Low	45,000	45,100	44,800	41,300	40,200	40,400	32,600
Average	45,280	45,370	45,120	42,820	42,130	42,050	35,700

Table VII (continued)

Specification No.	<u>50% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	45,100	45,100	45,500	39,100	41,400	35,300	43,900
2	45,200	44,800	44,100	40,100	39,000	42,300	37,100
3	32,800	45,300	44,700	37,900	36,000	42,200	38,100
4	45,100	43,900	37,800	37,000	41,200	33,900	40,700
5	45,300	43,600	45,300	40,600	42,000	35,700	38,800
6	40,600	45,000	43,200	43,700	39,900	37,500	37,800
7	44,900	43,800	45,200	40,100	41,800	37,100	38,900
8	45,300	44,900	39,500	39,800	41,800	38,400	39,400
9	45,100	43,300	41,800	39,300	43,600	37,800	45,000
10	45,200	44,500	44,300	38,900	42,300	38,400	37,700
High	45,300	45,300	45,500	43,700	43,600	42,300	45,000
Low	32,800	43,300	37,800	37,000	36,000	33,900	37,100
Average	43,460	44,420	43,140	39,660	40,900	37,860	39,740

Specification No.	<u>70% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	43,400	41,700	37,900	34,400	34,300	39,400	26,700
2	44,900	41,400	35,500	38,400	32,100	38,500	29,000
3	42,200	43,200	37,600	34,700	30,400	40,900	39,000
4	37,500	41,700	37,900	33,000	29,800	42,000	40,900
5	42,900	41,800	36,700	33,500	32,600	38,500	28,900
6	45,200	42,000	39,600	38,400	29,200	37,500	29,300
7	39,000	41,800	37,200	34,700	32,400	43,600	27,300
8	44,900	41,500	35,400	37,400	36,100	27,600	24,600
9	42,900	42,000	38,000	32,000	34,700	37,500	27,000
10	45,100	42,000	41,400	37,000	35,400	34,600	28,400
High	45,200	43,200	41,400	38,400	36,100	43,600	40,900
Low	37,500	41,400	35,000	32,000	29,200	27,600	24,600
Average	42,800	41,920	37,740	35,350	32,700	38,010	30,110

Table VIII. 6061-T6 Weld Strength Data--0.125-inch (1).

Specification No.	<u>0% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	47,400	47,500	46,500	45,800	48,000	43,500	40,600
2	45,000	45,100	47,100	46,200	47,500	44,300	41,800
3	47,300	45,000	46,700	45,900	47,700	44,100	43,500
4	47,400	45,400	47,400	46,000	45,400	44,200	41,000
5	46,500	47,600	46,800	45,400	45,200	44,200	47,200
6	47,400	45,400	47,700	46,900	48,000	41,900	41,400
7	47,800	47,200	47,700	45,400	45,200	41,700	41,600
8	47,100	45,300	44,200	46,100	47,500	41,100	42,000

Table VIII (continued)

Specification No.	<u>0% Mismatch</u>						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
9	47,500	47,700	46,900	46,200	45,400	44,000	41,900
10	44,900	45,300	48,100	45,600	47,200	43,500	42,000
High	47,800	47,700	48,100	46,900	48,000	44,300	47,200
Low	44,900	45,000	44,200	45,400	45,200	41,100	40,600
Average	46,830	46,150	46,190	45,950	46,710	43,250	42,300

(1) Tensile strength in pounds per square inch.

<u>15% Mismatch</u>							
1	47,000	45,000	44,300	44,500	45,500	46,400	44,800
2	46,300	37,600	46,400	45,300	34,600	45,100	46,300
3	47,100	46,000	45,700	45,500	46,000	48,400	45,300
4	46,900		47,200	44,200	48,000	46,500	46,600
5	46,500	44,900	45,600	45,400	45,200	45,600	46,000
6	46,700	45,200	46,200	45,600	46,900	46,700	46,700
7	47,100	47,100	45,300	45,200	46,900	45,800	45,600
8	46,700	44,900	46,600	45,400	46,500	45,900	46,600
9	46,700	46,500	45,700	45,000	47,400	46,100	46,900
10	46,700	47,000	47,200	45,700			44,900
High	47,100	47,100	47,200	45,700	48,000	48,400	46,900
Low	46,300	37,600	44,300	44,200	34,600	45,100	44,800
Average	46,770	44,980	46,020	45,180	45,220	46,280	45,970

<u>30% Mismatch</u>							
1	47,500	48,400	45,700	31,400	44,600	41,200	45,500
2	44,500	39,100	43,400	40,600	45,100	40,100	40,100
3	45,900	41,600	45,600	39,500	40,700	33,200	43,600
4	45,000	46,800	40,300	39,500	39,800	41,100	40,900
5	44,700	47,700	43,300	39,300	43,600	40,300	43,000
6	41,100	45,500	42,800	40,200	46,300	40,100	41,700
7	41,100	42,300	44,100	42,700	45,500	38,400	43,900
8	44,500	46,600	45,400	45,400	42,200	42,200	38,200
9	38,300	44,800	44,400	46,800	39,000	39,100	44,600
10	43,800	41,000	45,900	45,600	46,200	38,900	37,700
High	47,500	48,400	45,900	46,800	46,300	42,200	45,500
Low	38,300	39,100	40,300	31,400	39,000	33,200	37,700
Average	43,640	44,380	44,090	41,100	43,300	39,460	41,920

Table VIII (continued)

Specification No.	50% Mismatch						
	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
1	46,000		45,700	39,300	43,100	37,500	33,100
2	47,000	40,000	44,000	37,100	38,800	37,600	37,800
3	45,100	43,900	43,900	46,800	39,800	39,400	36,900
4	43,300	38,400	45,200	44,600	41,800	37,000	42,900
5	45,400	46,400	45,400	45,200	40,600	36,900	38,300
6	34,600	38,200	44,900	43,500	45,900	41,000	36,800
7	39,700	41,800	45,800	39,000	39,000	37,500	37,600
8	45,100	38,400	44,700	37,400	34,600	39,300	38,500
9	37,300	40,000	43,800	39,200	36,900	39,900	35,800
10			45,000	38,000	40,700	39,400	30,400
High	47,000	46,400	45,800	46,800	45,900	41,000	42,900
Low	34,600	38,200	43,800	37,100	34,600	36,900	33,100
Average	42,610	40,890	44,840	41,010	40,120	38,550	37,710

## 70% Mismatch

1	43,900	41,400	40,700	35,100	37,500	36,400	37,600
2	44,300	41,400	40,900	32,900	37,900	30,900	38,100
3	40,700	40,700	40,400	36,500	39,500	36,500	40,700
4	41,700	41,700	40,700	35,700	39,300	33,200	36,900
5	42,000	41,600	40,300	33,400	37,400	35,800	26,300
6	38,900	40,000	42,400	39,100	30,500	38,400	31,100
7	43,100	41,800	40,400	40,000	37,400	30,400	42,200
8	40,500	41,400	42,000	35,300	38,200	33,700	39,600
9	43,700	41,000	39,900	31,300	39,900	36,800	34,100
10	41,200	41,800	39,900	35,600	39,700	37,200	40,400
High	44,300	41,800	42,400	40,000	39,900	38,400	42,200
Low	38,900	40,000	39,900	31,300	30,500	30,400	26,300
Average	42,000	41,280	40,760	35,480	37,730	34,930	36,700

Table IX. Statistical Analysis of Data for 0.100-inch 6061-T6.

Mismatch %	Code (1)							
	Symbol	<u>P<sub>0</sub></u>	<u>P<sub>1</sub></u>	<u>P<sub>2</sub></u>	<u>P<sub>3</sub></u>	<u>P<sub>4</sub></u>	<u>P<sub>5</sub></u>	<u>P<sub>6</sub></u>
0	N	10	10	10	10	10	10	10
	X	45,000	45,000	42,800	43,200	41,100	42,500	36,200
	L							
	$\bar{X}$	45,260	45,260	44,840	44,440	43,690	43,690	41,540
	C (%)	0.3	0.3	3.2	1.9	4.2	2.0	9.2
	V							
99	W	44,940	44,940	41,500	43,510	39,410	41,650	32,640



Table IX (continued)

Mismatch %	Code (1) Symbol	<u>P</u> <u>0</u>	<u>P</u> <u>1</u>	<u>P</u> <u>2</u>	<u>P</u> <u>3</u>	<u>P</u> <u>4</u>	<u>P</u> <u>5</u>	<u>P</u> <u>6</u>
15	N	10	10	10	10	10	10	10
	X	44,600	45,000	43,500	43,000	42,300	42,700	42,400
	$\bar{X}_L$							
	$\bar{X}$	45,270	45,210	44,580	44,630	43,490	44,250	44,210
	$C_V$	1.0	0.4	1.6	2.6	1.9	2.6	2.8
	$W_{99}$	44,210	44,790	42,920	41,930	41,560	41,570	41,320
30	N	10	10	10	10	10	10	10
	X	45,000	45,100	44,800	41,300	40,200	40,400	32,600
	$\bar{X}_L$							
	$\bar{X}$	45,280	45,370	45,120	42,820	42,130	42,050	35,700
	$C_V$	0.3	0.4	0.4	2.5	3.2	2.8	6.2
	$W_{99}$	44,970	44,950	44,700	40,320	38,990	39,310	30,540
50	N	10	10	10	10	10	10	10
	X	32,800	43,300	37,800	37,000	36,000	33,900	37,100
	$\bar{X}_L$							
	$\bar{X}$	43,460	44,420	43,140	39,660	40,900	37,860	39,740
	$C_V$	17.6	1.8	8.8	4.8	8.6	7.5	4.7
	$W_{99}$	25,640	42,560	34,300	35,220	32,700	31,240	35,390
70	N	10	10	10	10	10	10	10
	X	37,500	41,400	35,400	32,000	29,200	27,600	24,600
	$\bar{X}_L$							
	$\bar{X}$	42,800	41,920	37,740	35,350	32,700	38,010	30,110
	$C_V$	8.8	0.9	4.4	6.8	7.6	19.6	13.1
	$W_{99}$	34,030	41,040	33,870	29,750	26,910	20,650	20,920

- (1) N = number of specimens  
 $\bar{X}_L$  = minimum value of series  
 $\bar{X}$  = average (mean) of series  
 $C_V$  = Coefficient of variation %  
 $W_{99}$  = estimated minimum value for  
99% confidence level.

Table X. Statistical Analysis of Data for 0.125-inch 6061-T6.

Mismatch (%)	Code <sup>(1)</sup> Symbol	$P_0$	$P_1$	$P_2$	$P_3$	$P_4$	$P_5$	$P_6$
0	N	10	10	10	10	10	10	10
	$X_L$	44,900	45,000	44,200	45,400	45,200	41,100	40,600
	$\bar{X}$	46,830	46,150	46,910	45,950	46,710	43,250	42,300
	$C_V(\%)$	2.9	1.8	4.2	0.8	2.4	3.6	2.9
	$W_{99}$	43,670	44,210	42,320	45,090	44,100	39,610	39,440
15	N	10	9	10	10	9	9	10
	$X_L$	46,300	37,600	44,300	44,200	34,600	45,100	44,800
	$\bar{X}$	46,770	44,980	46,020	45,180	45,220	46,280	45,970
	$C_V$	0.7	12.1	2.7	1.7	17.4	1.8	1.8
	$W_{99}$	46,010	32,280	43,120	43,390	26,870	44,340	44,040
30	N	10	10	10	10	10	10	10
	$X_L$	38,300	39,100	40,300	31,400	39,000	33,200	37,700
	$\bar{X}$	43,640	44,380	44,090	41,100	43,300	39,460	41,920
	$C_V$	8.7	8.5	6.2	16.8	5.6	11.4	7.2
	$W_{99}$	34,740	35,580	37,690	25,100	37,650	28,990	34,870
50	N	9	8	10	10	10	10	10
	$X_L$	34,600	38,200	43,900	37,100	34,600	36,900	33,100
	$\bar{X}$	42,610	40,890	44,840	41,010	40,120	38,550	37,710
	$C_V$	13.9	5.2	1.5	6.8	9.8	3.1	8.8
	$W_{99}$	28,810	35,940	43,270	34,510	30,970	35,760	29,940
70	N	10	10	10	10	10	10	10
	$X_L$	38,900	40,000	39,900	31,300	30,500	30,400	26,300
	$\bar{X}$	42,000	41,280	40,760	35,480	37,730	34,930	36,700
	$C_V$	5.3	2.2	1.5	8.4	13.7	9.3	20.2
	$W_{99}$	36,800	39,160	39,340	28,530	25,680	27,360	19,450

- (1) N = number of specimens  
 $X_L$  = minimum value of series  
 $\bar{X}$  = average (mean) of series
- $C_V$  = coefficient of variation, %  
 $W_{99}$  = estimated minimum value for 99% confidence level.

## APPENDIX A

SUMMARY OF WELD TEST DATA COMBINED EFFECTS OF MISMATCH  
AND POROSITY ON 0.190-IN. THICK 2014-T6 IN THE  
AS-WELDED CONDITION

Table A-I. Weld Strength Data--P<sub>0</sub> Porosity.

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	45,000	36,600	36,100	29,700	30,000
	48,300	36,500	33,600	30,500	27,000
	45,300	36,100	37,200	32,200	26,800
	49,300	43,500	35,000	33,100	28,600
	49,600	39,200	35,200	31,700	25,300
	46,700	46,400	35,500	31,500	28,300
	47,200	35,700	33,500	28,200	25,100
	48,900	34,500	36,300	33,200	25,900
	51,400	37,200	33,200	29,600	29,000
	47,400	37,400	33,500	28,000	24,900
	48,700	37,100	35,700	32,000	24,900
	47,600	43,400	34,500	29,800	25,700
	47,400	47,300	36,600	31,400	24,800
	50,900	43,200	36,100	30,200	29,900
	46,300	36,500	33,800	30,600	24,600
	51,300	45,900	35,800	31,400	24,800
	47,900	44,000	36,400	29,400	26,900
	45,700	45,000	35,100	30,800	26,700
	46,500	39,200	35,700	33,000	27,900
	50,100	40,100	34,100	31,700	24,400
	49,600	44,200	35,800	31,500	24,600
		44,000			26,400
N	21	22	21	21	22
Low	45,000	34,500	33,200	28,000	24,400
Average	48,100	40,600	35,800	30,900	26,400
High	51,400	47,300	37,200	33,200	30,000

Table A-II. Weld Strength Data--P<sub>1</sub> Porosity.

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	43,700	47,400	32,100	32,600	23,400
	50,900	46,600	37,800	33,300	27,200
	49,300	40,100	35,700	30,400	26,000
	45,800	41,800	36,600	33,900	30,400
	47,900	34,700	31,400	34,700	24,400
	48,600	46,500	37,200	30,800	25,200
	49,400	45,500	41,900	31,500	26,000
	43,100	45,900	35,100	34,000	22,500
	51,200	37,300	36,700	33,400	26,500

Table A-II (continued)

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	48,300	39,400	33,400	32,600	26,500
	48,600	38,400	32,700	34,100	22,400
	48,400	47,100	35,200	31,300	23,800
	49,000	35,100	33,300	30,400	26,000
	48,800	43,000	36,000	30,500	23,600
	46,300	35,900	35,800	32,400	22,000
	48,600	41,500	35,800	32,100	23,300
	44,600	35,500	37,200	32,600	29,700
	44,800	38,300	40,600	34,500	26,200
	50,700	42,100	37,400	31,000	27,700
	47,500	38,000	40,100	30,200	24,700
		38,300			
N	20	21	20	20	20
Low	43,100	34,700	31,400	30,200	22,000
Average	47,800	40,900	36,100	32,300	25,400
High	51,200	47,400	41,900	34,700	30,400

Table A-III. Weld Strength Data--P<sub>2</sub> Porosity.

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	44,200	30,100	28,000	30,100	32,400
	42,500	32,800	32,300	25,300	24,000
	44,900	44,500	35,300	25,500	25,600
	45,400	36,600	32,700	29,500	24,100
	45,800	41,700	32,700	26,500	25,000
	47,700	46,600	32,300	32,400	25,200
	46,800	39,300	37,700	27,500	26,200
	46,700	37,900	35,300	31,700	25,200
	44,000	44,300	38,200	29,100	27,100
	47,300	34,900	32,900	27,900	24,900
	47,300	36,200	35,900	30,400	25,800
	47,500	35,400	36,200	30,400	26,600
	40,600	37,300	34,300	28,300	30,900
	46,000	38,700	32,300	25,200	28,400
	48,700	35,000	33,500	28,100	26,400
	46,200	35,000	35,700	27,000	
	43,800	47,900	34,400	30,700	
	46,700	38,600	33,000	29,600	
	48,100	40,600	32,800	25,900	
	44,200	46,700	30,200	29,000	
	45,300	38,200	32,600		
			36,800		

Table A-III (continued)

N	21	21	22	20	15
Low	40,600	30,100	28,000	25,200	24,000
Average	45,700	39,000	33,900	28,500	26,500
High	48,700	47,900	38,200	32,400	32,400

Table IV. Weld Strength Data--P<sub>3</sub> Porosity.

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	45,000	40,100	35,300	35,500	26,800
	46,500	45,800	33,100	30,700	25,100
	41,100	36,400	33,000	33,900	25,600
	40,600	46,300	34,200	31,800	25,300
	44,200	42,100	28,500	33,200	26,300
	42,100	44,900	31,700	37,700	26,600
	44,900	39,700	30,600	31,700	26,400
	45,700	41,300	30,400	31,900	24,800
	45,200	36,200	28,200	34,800	27,500
	38,300	38,700	32,000	31,500	26,800
	40,100	33,000	31,000	35,000	26,400
	43,700	39,200	27,900	34,200	26,300
	41,500	37,000	30,200	31,200	26,000
	44,100	47,400	36,000	29,700	25,300
	39,600	45,600	33,600	32,100	28,600
	42,800	34,000	31,700	31,900	23,900
	36,700	36,000	34,600	33,000	24,700
	40,500	46,300	30,800	28,400	26,400
	42,800	47,100	30,300	33,200	
	40,900	42,400	32,500	32,300	
N	20	20	20	20	18
Low	36,700	33,000	27,900	28,400	23,900
Average	42,300	41,000	31,800	32,700	26,000
High	46,500	47,400	36,000	37,700	28,600

Table A-V. Weld Strength Data--P<sub>4</sub> Porosity.

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	46,300	40,800	32,600	31,200	24,800
	48,100	43,000	32,400	23,900	27,600
	46,700	45,300	30,300	30,600	25,600
	40,200	38,300	31,400	31,900	26,600
	40,600	41,400	34,500	32,000	25,900
	42,100	41,900	35,600	24,400	25,900
	45,200	38,300	33,900	31,800	25,500
	46,000	44,400	31,000	32,100	30,500
	40,200	46,000	34,000	33,800	27,300
	43,600	39,100	30,400	32,600	23,500
	42,800	42,000	32,800	28,000	24,500
	44,100	36,000	35,300	22,500	24,700
	43,900	46,400	35,700	32,500	22,300
	41,200	45,700	31,000	32,500	27,500
	41,400	35,000	29,900	26,000	27,200
	46,000	41,700	30,700	32,800	24,700
	44,200	39,300		32,400	23,600
	41,500	37,400		31,500	25,100
	44,100	39,400		34,100	24,600
	39,800	37,300		33,500	24,200
N	20	20	16	20	20
Low	39,800	35,000	29,900	22,500	22,300
Average	43,400	40,900	32,600	30,500	25,600
High	48,100	46,400	35,700	33,800	30,500

Table A-VI. Weld Strength Data--P<sub>5</sub> Porosity

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	39,200	36,900	31,200	25,000	25,600
	48,600	34,000	31,900	24,600	28,100
	45,400	35,400	32,500	32,600	27,500
	42,600	44,100	31,900	35,500	27,800
	43,500	40,800	32,800	28,000	26,700
	40,300	44,200	35,200	28,500	26,700
	45,200	43,100	32,900	27,000	25,000
	40,900	46,500	32,000	27,400	24,700
	38,700	44,700	28,100	29,400	27,000
	39,900	46,100	36,300	29,700	24,700
	40,900	42,400	32,100	27,700	26,000

Table A-VI (continued)

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	42,000	46,800	31,000	29,300	25,300
	40,900	35,000		28,700	25,000
	40,300	41,700		29,900	22,000
	44,300	39,600		28,900	24,400
	42,700	43,100		29,600	23,500
	40,500	37,000		28,900	22,600
	46,200	40,200			25,300
	43,300	42,800			
	40,200	38,600			
N	20	20	12	17	18
Low	38,700	34,000	28,100	24,600	22,000
Average	42,300	41,100	32,300	28,900	25,500
High	48,600	46,500	36,300	35,500	28,100

Table A-VII. Weld Strength Data--P<sub>6</sub> Porosity

<u>Mismatch</u>	<u>0%</u>	<u>15%</u>	<u>30%</u>	<u>50%</u>	<u>70%</u>
	39,800	43,500	34,200	32,700	24,300
	42,500	39,900	30,200	29,400	25,900
	45,500	38,200	30,600	37,000	26,100
	42,900	40,300	31,900	38,400	24,400
	39,400	39,800	36,700	25,600	25,100
	45,000	40,000	34,400	29,700	24,900
	44,500	37,900	32,100	31,600	26,500
	42,000	40,400	39,000	34,100	25,300
	42,300	37,300	35,700	31,100	26,600
	42,200	37,400	40,100	30,700	24,600
	43,300	38,700	34,500	33,700	25,200
	42,800	42,200	33,900	30,600	27,600
	42,400	42,300	35,800	33,400	27,800
	44,300	46,500	32,200	30,100	29,200
	43,400	36,800	33,200		23,000
	42,400	37,500	31,000		24,100
	45,200	37,900	32,500		23,500
	41,900	37,700	34,900		27,400
	45,200	44,000	39,600		29,300
	45,400	38,700			23,900
N	20	20	19	14	20
Low	39,400	36,800	30,200	25,600	23,000
Average	43,100	39,800	34,300	32,000	25,700
High	45,500	46,500	40,100	38,400	29,300



## DISCUSSION

Mr. Jackson: One of the things I'm going to ask to start off the discussion: do you have any guess as to what percentage of lack of material you have in a P-6 porosity? Would it be 3 percent?

Mr. Bandelin: You refer to cross sectional area?

Mr. Jackson: Density.

Mr. Bandelin: I would say our P-6 level goes up in the area of 5 to 6 percent. Progressively from P-0 down, you'll find it goes up to a maximum of 5 to 6 percent cross-sectional reduction.

Mr. Jackson: In many of those curves, you showed a drop of about roughly 10 percent in tensile strength going to maximum porosity.

Mr. Bandelin: Ten percent to fifteen percent maximum.

Mr. Jackson: Good, we have another question.

Mr. Bandelin: Either they didn't understand it, or it was no good. Which is it?

Mr. Brown: If I understood you correctly, I think you have indulged in some dangerous thinking, and I'd like to get it clarified. First of all, I'd like to know exactly what you're trying to prove since we know that porosity and mismatch are both, taken alone or together, dangerous things. When you made the statement outright that these didn't have any particular effect, or didn't hurt the strength---even this heavy porosity---were you talking about dynamic load or only the limited tensile tests you were doing? Because I think you're walking on quicksand.

Mr. Bandelin: I had reference to that on the 2014 heavy material where mismatch played a heavy role in failure. From the many tests that I've run prior to this, on porosity by itself, and on mismatch by itself, I must repeat---whether I'm being facetious with my statement or not---that the heavier you go in the 2014 alloys, the more important the mismatch and the more critical it becomes to you from a failure aspect; much more than the porosity levels that we're finding in there caused by this hydrogen or many, many other things.

New Speaker: We in manufacturing don't walk on water, and whether we like it or not, we end up with mismatch and the gaps and this type of thing. During the Bomarc program in Boeing, we found that some 50 percent of all weld repairs were made on repairs. We've done a lot of study of the effect of re-repairing on degradation of joint properties. I find it difficult to believe that we're ever going to be able to build large boosters with extensive inches of welding without having to do some repair. And almost undoubtedly, some of these repair areas are going to be the weak points in the whole chain. So let's look at them practically. Let's not make repairs; the chances are that repair is going to be worse than the original defect.

Mr. Bandelin: I think you got my point very well; that's what I tried to put over, one of the points.

Mr. Saperstein: I think I'll have to go along with Hi Brown here, that some of the comments that you have made are undoubtedly valid; however, I think we have to learn a lot more, especially as Hi points out, about dynamic loading conditions. It is not only the total concentration of porosity that may be important, but also the proximity of a pore to a free surface, that is, the distribution of the porosity. I think that in some work that we have done there is some indication that a pore can be generated into a crack, and a crack can be very damaging in low cycle fatigue behavior. So, I think we have to be a bit cautious.

Mr. Bandelin: There's no doubt that you're correct. However, I don't see much published, and I'm one that loves to read, on the combined effects of porosity and mismatch. I don't ever recall seeing any paper, ever presented or written, where they gave results. What I'm trying to put forth to everyone of you, this is a start, gentlemen. Let's not continuously try to degrade what we have manufactured, but let's find out if we're making correct assumptions in removing certain things that could degrade them even worse than they are. And I'm trying to put the thought into your head, and everyone's head, that more work should be done in this area. And as I said, I don't mean to be facetious, but if I tread on your toes, don't whine.

Mr. Brown: You still haven't answered my question---what are you up to--- is the first question. Secondly, I don't think there is anything new or earth-shaking in the fact that the thicker the material, the more sensitive it is to notch ductility, which is the effect you have from a mismatch. I think it's dangerous to combine that knowledge, which you already have, with the knowledge which we do not have on the effect of this combination. What I'm trying to find out is why are you trying to combine the two. Is it a problem you're having consistently or what exactly are you up to?

Mr. Bandelin: Being a foundryman, I guess you're not as familiar with the problem of building the missiles as many of us are. (Laughter) I heard the man from Boeing state, about the Bomarc, the problem they have on repair; I know the problems the NASA people are having down here with Saturn fabrication; I know the problems that they're having at Michoud on mismatches, and I know about many other companies the same as you. I must admit, they're not all the same materials; some of them are 2014, 6061, some are 2219, you name it. What I tried to point out is that this condition does occur. It varies with the type of material you have and the conditions of the material. And I tried to point out that in the 2014, it was worse, if I can be so sarcastic as to say this, when we got into the higher mismatch conditions than it was in the 6061. And I also mentioned that it was more prevalent as the heavier the material became in our studies. Now, you may have studies that are different---all of us think a little differently---I've heard sixteen men talking on porosity formation, how porosity came about, and I've heard different opinions of different people about how the hydrogen affects certain things. This is my thought and my studies, and I'm only trying to convey them to you for your help if you need it.

Mr. Jackson: Another question. Right here; all right, Frank.

Comment: I only have one comment that I would like to add. The repairing of 2014 or any other material does not necessarily destroy the part. You can eliminate a great deal of the work in regard to distortion and mechanical degradation by simply packing the prepared area in dry ice.

Mr. Jackson: There is one question down here.

Mr. Wuenscher: I wanted to emphasize, also, that whenever the parts are all million dollar pieces, and you have porosity and mismatch, you just have to make it work. It is no longer just a question of weld technology. I think that we must start out with a 'weld-repair technology'. I think this presentation is a good start.

Mr. Jackson: Jim says we're behind schedule now, so this is it. Thanks Bernie.

SELF-COMPENSATING GAS TUNGSTEN-ARC WELDING

By

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## INTRODUCTION

This talk is about an automatic welding process that is responsive to irregular conditions that occur during the welding operation as well as non-uniform conditions existing prior to welding. As we see it, the main problem in automatic welding is the welding operation itself generates forces that continually tend to create variable thermal conditions as we proceed along the joint. Either these changes must be minimized by elaborate fixturing - which is an expensive undertaking - or an intelligence and control system that can dynamically react to them is required. While this problem has been the subject of recent industry study, to the authors' best knowledge, no automatic welding equipment is yet available. The point of this paper is that Republic's Self-Compensating TIG method is somewhat different than the conventional approach towards attaining automatic welding.

The remainder of this talk will be divided into three parts. First we will briefly review some welding theory, then we will present Republic's concept, and finally we will discuss the results of laboratory tests supporting our thesis. As you may have gathered the Republic process is presently in the development stage.

## WELDING THEORY

The shape of a weld deposit is controlled by maintaining a localized "thermal balance". When the thermal balance is disturbed, the power required to produce an optimum quality weld changes.

Now the term "thermal balance" is admittedly nebulous, especially since we do not intend to propose any boundary conditions. But we submit that a very good indicator or measure of thermal activity during the welding operation is the surface of the liquid in the weld crater. If the crater surface is accepted as a significant weld parameter we then ask, why does it vary during the welding operation? This occurs in most cases because the localized sensible heat sink is disturbed; for example, the workpiece is making erratic contact with the weld fixture. In any case we assume that the weld crater responds to a change in the thermal balance.

Now consider the power consumed in a welding arc. Refer to Figure 1. Commercial welding power sources are designed to provide an explicit relationship between terminal voltage and current. With the exception of constant current and constant voltage sources, a change in one parameter results in a definitive response in the other. This static load volt-ampere relationship curve is known as the power source characteristic.

For any specified gas atmosphere, electrode composition and shape, distance between electrode and anode, and workpiece composition, every arc exhibits a specific volt-ampere relationship. Any change in current at a constant arc length is accompanied by a change in voltage. On the other hand, an entirely new volt-ampere relationship is defined if the arc length is changed. This relationship between arc current, arc voltage and arc length is called the arc characteristic; it depends entirely on the prevailing welding conditions and is totally independent of the type of power source.

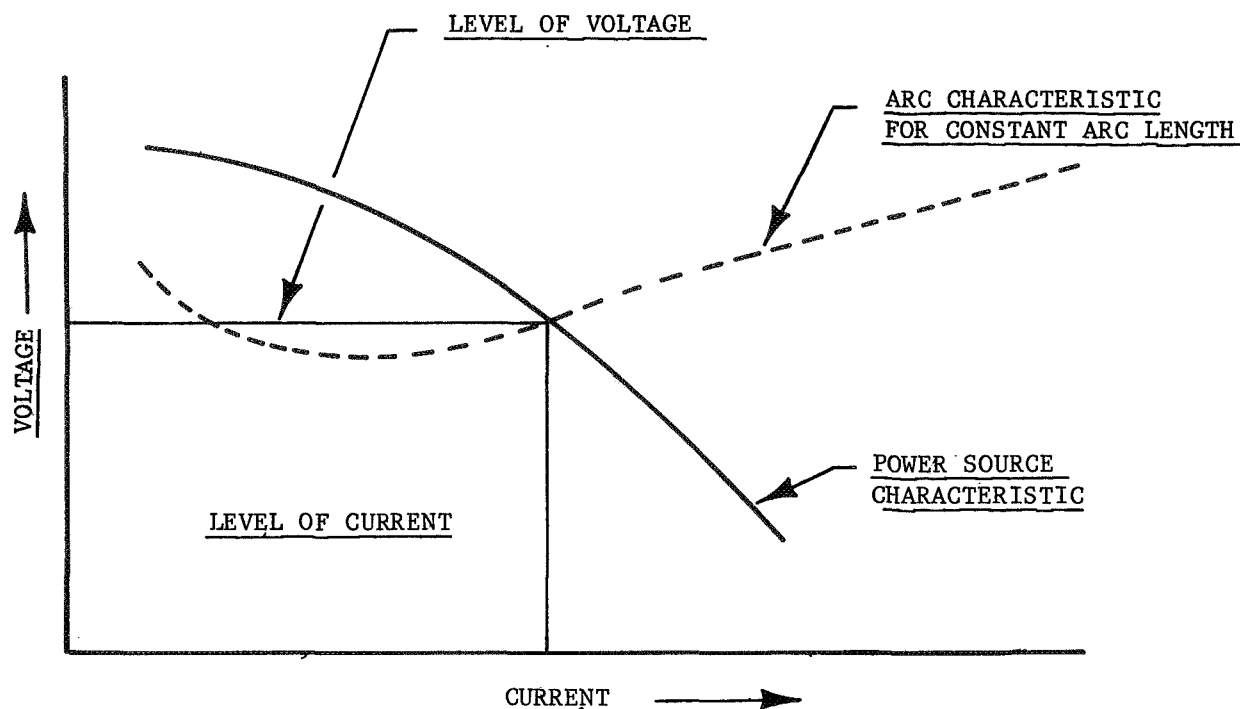


Figure 1. Combined Power Source Characteristic and Arc Characteristic Curves

The particular level of current and voltage at which a stable welding arc operates is determined by the intersection of the two characteristic curves.

#### SELF-COMPENSATION SYSTEM

The self-compensation system discussed herein is designed to automatically regulate the power input to the workpiece by using the welding arc and the static load characteristic of the power source as sensing and control devices respectively.

The first requirement of all automatic welding systems is to generate an error signal. That is, a device is needed to continually "measure" a weld characteristic and to compare this intelligence with a standard.

A reasonable plan seems to be to measure the crater depth with the welding arc. For the sake of discussion, the stipulation is made that proximity between the electrode and workpiece is accurately maintained without using the arc voltage to control this function. When this requirement is satisfied, the arc length can be used as an instrument for

measuring the weld crater. More important, a change in arc length is indicative of a change in the immediate welding conditions. Thus employed, the welding arc is itself a simple, durable, reproducible, quick acting sensing device.

Referring to Figure 2, it can be seen that the intersection of the power source characteristic curve with the new arc characteristic curve determines the welding system response to an arc length variation. Further inspection of Figure 2, reveals that either an increase or decrease in power can result depending entirely upon the slope of the power source characteristic curve. From this we induce that a power level can be selected prior to arc initiation and established during welding for any condition that causes a predictable variation in arc length.

The self-compensating TIG mechanism can now be defined more precisely. As a change in welding conditions is detected by the arc, this signal combined with a carefully selected power source characteristic automatically adjust the power supplied to the weld to counteract that change.

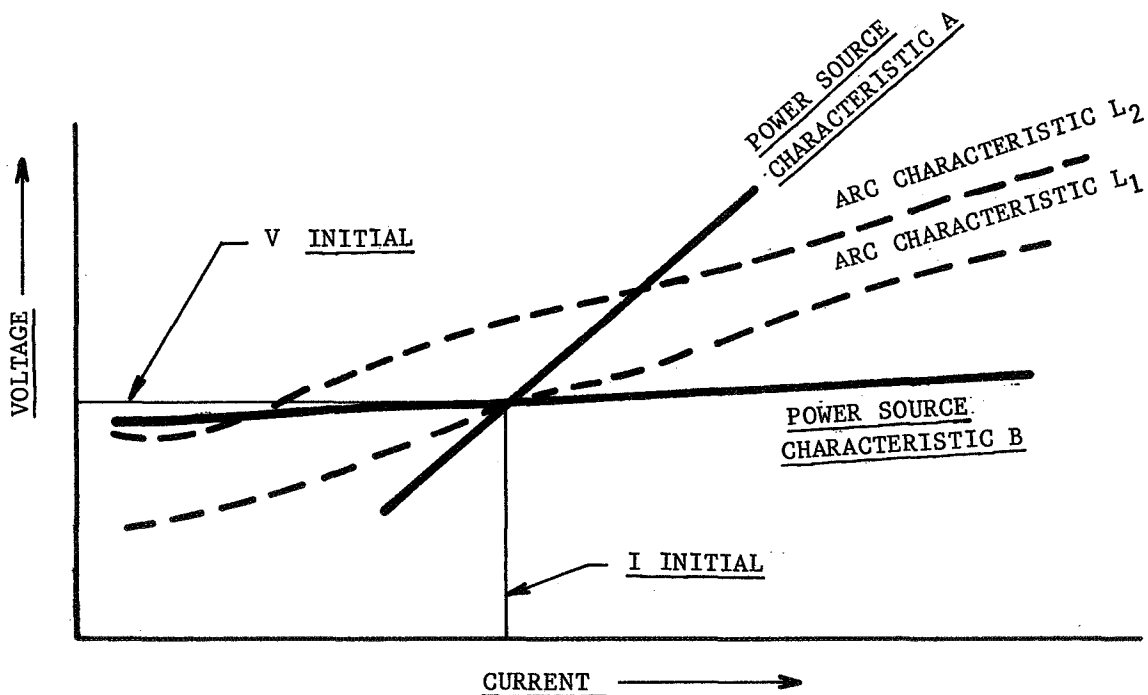


Figure 2. Effect of Power Source Characteristic

But, how do we know what the power source characteristic should be for a particular situation?

Consider a butt joint, shown in Figure 3, in which the root opening varies as welding progresses along the joint. Figure 4 shows two test specimens with uniform root openings which are respectively equal to the root openings at sections A-A and B-B. Both the heat sink and the power required to make a satisfactory weld at any section in the test specimens are assumed to be equivalent (neglecting transient effects) to the corresponding section in the original weld joint. Weld schedules are then determined for the test specimens in which the differences between schedules are restricted to current, voltage, and arc length (distance between tip of tungsten and weld crater) and the other parameters such as travel speed, wire feed speed, and proximity (distance between tip of tungsten and work-piece surface) are constants. Referring to Figure 5, note that points P and Q represent the welding schedules for the test specimens as well as satisfactory power levels for sections A-A and B-B, respectively. Assuming a linear relationship between joint condition and required power, the best curve (or line) that can be fitted to the points representing the welding schedules (in this case points P and Q) defines the power requirements for the given conditions. This curve is also the required power source characteristic.

When the self-compensation system is in effect, how does the continually changing power level remain synchronized with the joint condition for which it is intended? Remember that we use arc length to measure a particular welding condition. Through the intersection of the two characteristic curves the power level is also tied to arc length. Thus the effectiveness of the welding system is dependent on the accuracy of the arc length reproduction.

The Republic welding system can be summarized as follows:

- (1) Adverse conditions such as variable root opening and heat sink are reflected in changes in the weld crater.
- (2) The changes in the crater size are sensed by the arc as changes in arc length.
- (3) The volt-ampere characteristic of the power source is selected in such a manner that the change in arc length results in an automatic and counteracting power adjustment.

#### DEMONSTRATION OF SELF-COMPENSATION TRENDS

A premise of the welding system is that with constant proximity, the arc length will be responsive to fluctuations in the weld crater caused by a non-uniform heat sink. Various experiments performed in Republic's welding laboratory support the validity of this assumption.



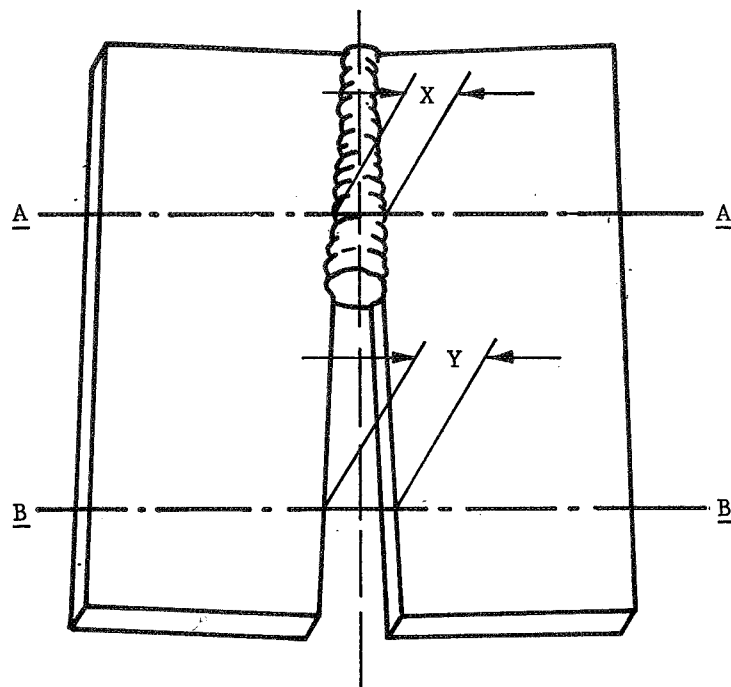


Figure 3. Fitup Variation as Welding Progresses

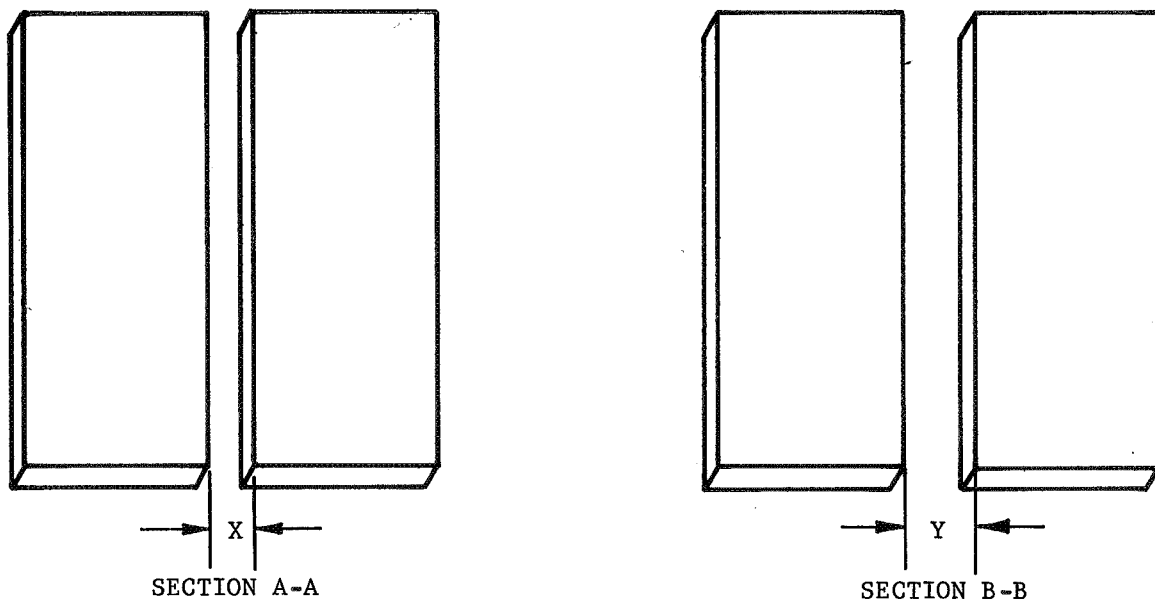
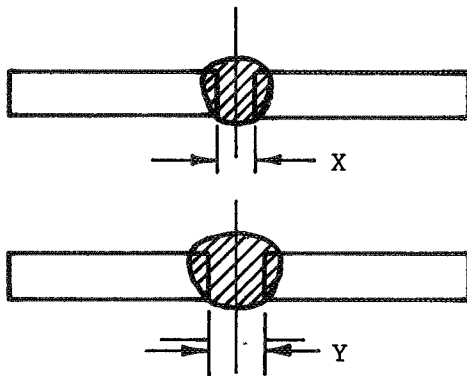


Figure 4. Equivalent Heat Sinks



# WELDING SCHEDULE

VARIABLES	CONSTANTS
$V_x, I_x, L_x$	PROXIMITY
$V_y, I_y, L_y$	TRAVEL SPEED
	WIRE FEED SPEED

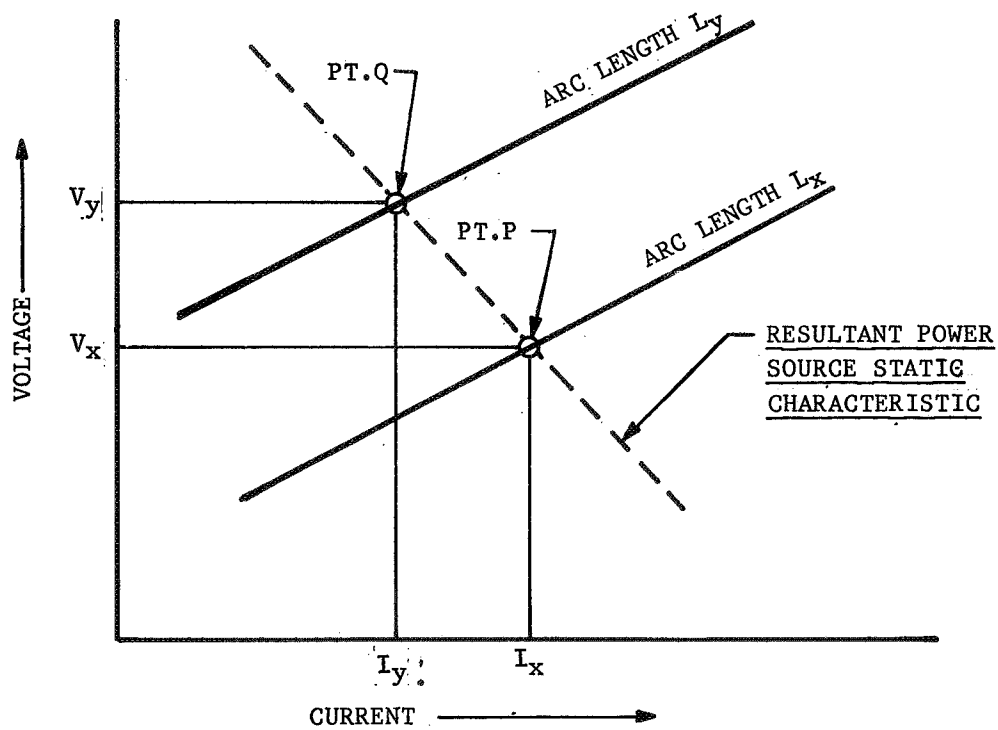


Figure 5. Power Source Status Characteristic Determination on the Basis of Optimum Welding Schedule.

### Effect Of Rate Of Heat Input

It was demonstrated that arc length changed in response to variation in the rate of heat input to the weld. Several tests were made in which a fusion bead was welded on 1/4 inch aluminum plate. All welding parameters were held constant during the test with the exception of travel speed which was intentionally varied. The distance between tungsten tip and workpiece (proximity) varied from test-to-test. Figure 6 is representative of the welding current response to the deliberate increase and decrease in travel speed. It is Republic's interpretation that the change in current resulted from a change in arc length-in accordance with the previously described interaction between power supply and arc length characteristics - which in turn had been caused by a change in the weld crater created by the intentional variation of travel speed.

### Effect Of Heat Sink

Another series of tests were designed to show the effect of a variable heat sink. Fusion welds were made along the longitudinal center line of a specially designed aluminum specimen. The geometry of the specimen and the observed variation in current as welding progressed is shown in Figure 7. Observe that in every case the current decreased when the arc passed an area with a reduced adjacent mass. The analysis of the results is the same as in the previous experiment, that is, the arc length changed in response to a disturbance of the weld thermal balance.

### Effect Of The Power Source Static Characteristic

A simplified empirical technique for selecting a particular characteristic was demonstrated by conducting the following experiment. A power source volt-ampere characteristic curve was required that would provide constant penetration in an 1/8 inch stainless steel workpiece while the proximity (distance between tungsten tip and workpiece) was varied between 1/16 and 1/4 inches.

Several test plates were fusion welded at different values of current and voltage for each specific proximity investigated. Weld penetration was measured and the current versus penetration relationship for constant proximity was plotted to determine the curves shown in Figure 8a. The proximity-volt-ampere characteristics for the prevailing welding conditions (stainless steel workpiece, argon gas, 2 percent thoriated tungsten electrode, etc.) was also determined and the curves plotted as shown in Figure 8b.

The desired power source characteristic was thereupon determined graphically by transferring the current values obtained at full penetration for each proximity to the corresponding proximity-volt-ampere curve (Figures 8a and 8b). In this instance the desired power source characteristic should display a rising slope of 45 volts per 100 amperes for the range of proximity variations covered.

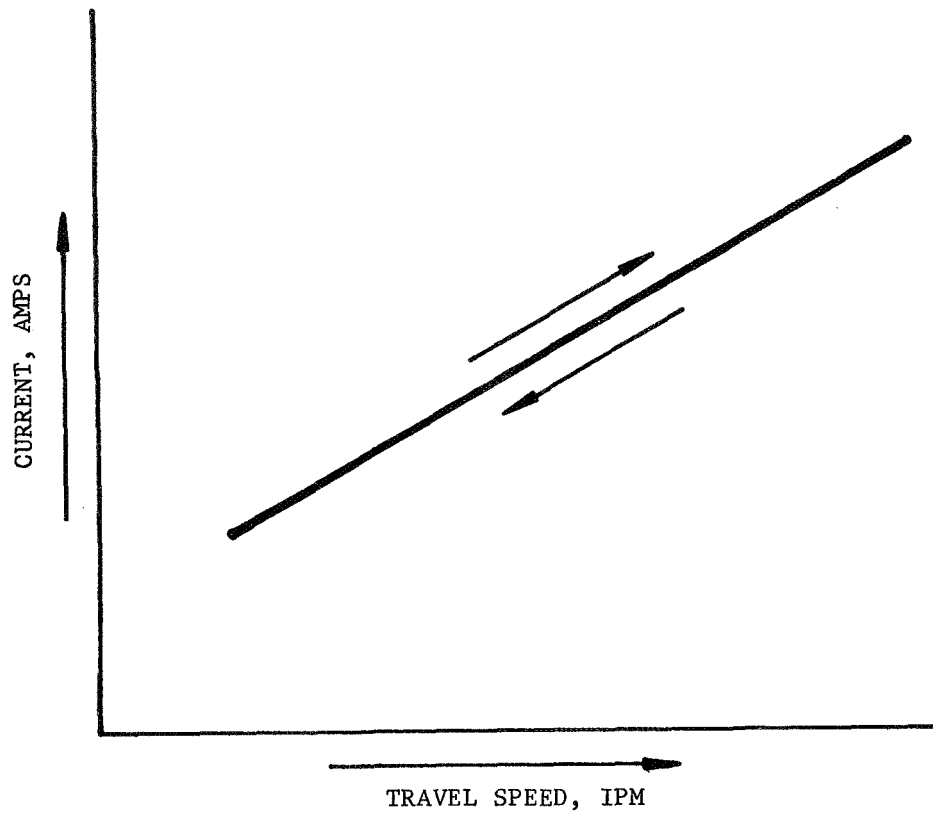
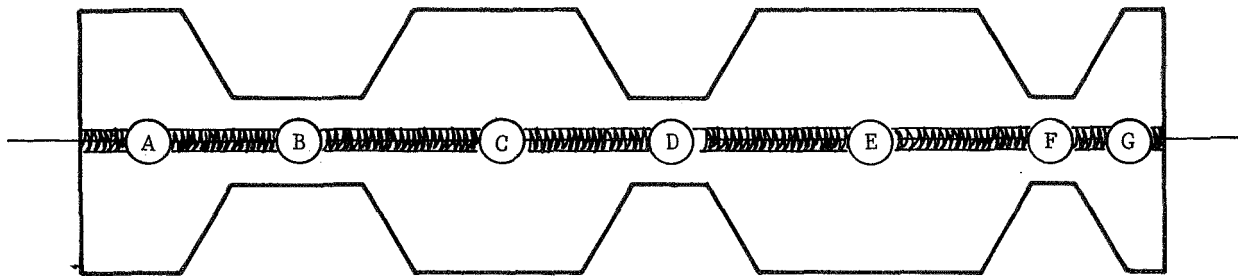
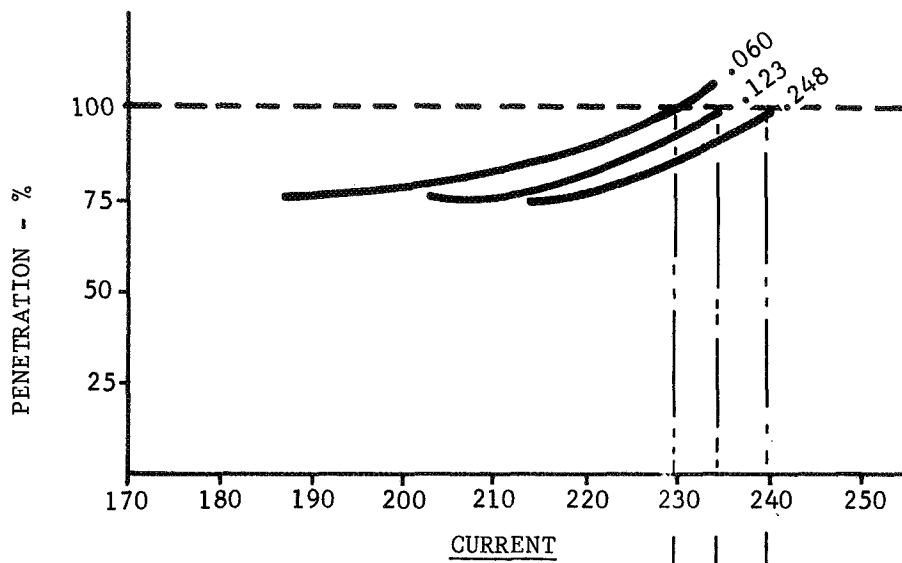


Figure 6. Welding Current Response To Deliberate Change in Travel Speed

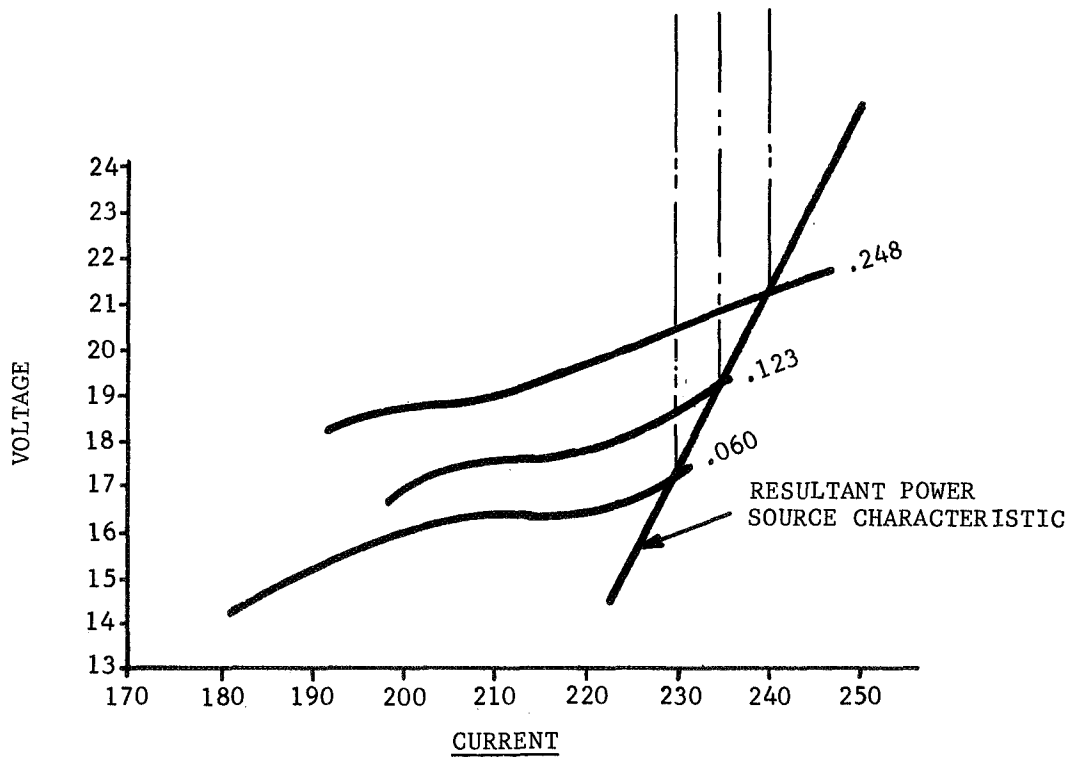


CONDITION	CURRENT						
	A	B	C	D	E	F	G
.005 IN. ARC LENGTH; 15.5 IPM; POWER SOURCE CHAR. "A"	265	260	275/280	265/270	275/285	275	280
.005 IN. ARC LENGTH; 10 IPM; POWER SOURCE CHAR. "B"	230	220	240/245	220	230/240	220	240
.005 IN. ARC LENGTH; 10 IPM; POWER SOURCE CHAR. "C"	220	205	225/215	205/200	210/220	200/195	210

Figure 7. Welding Current Response to Change in Heat Sink



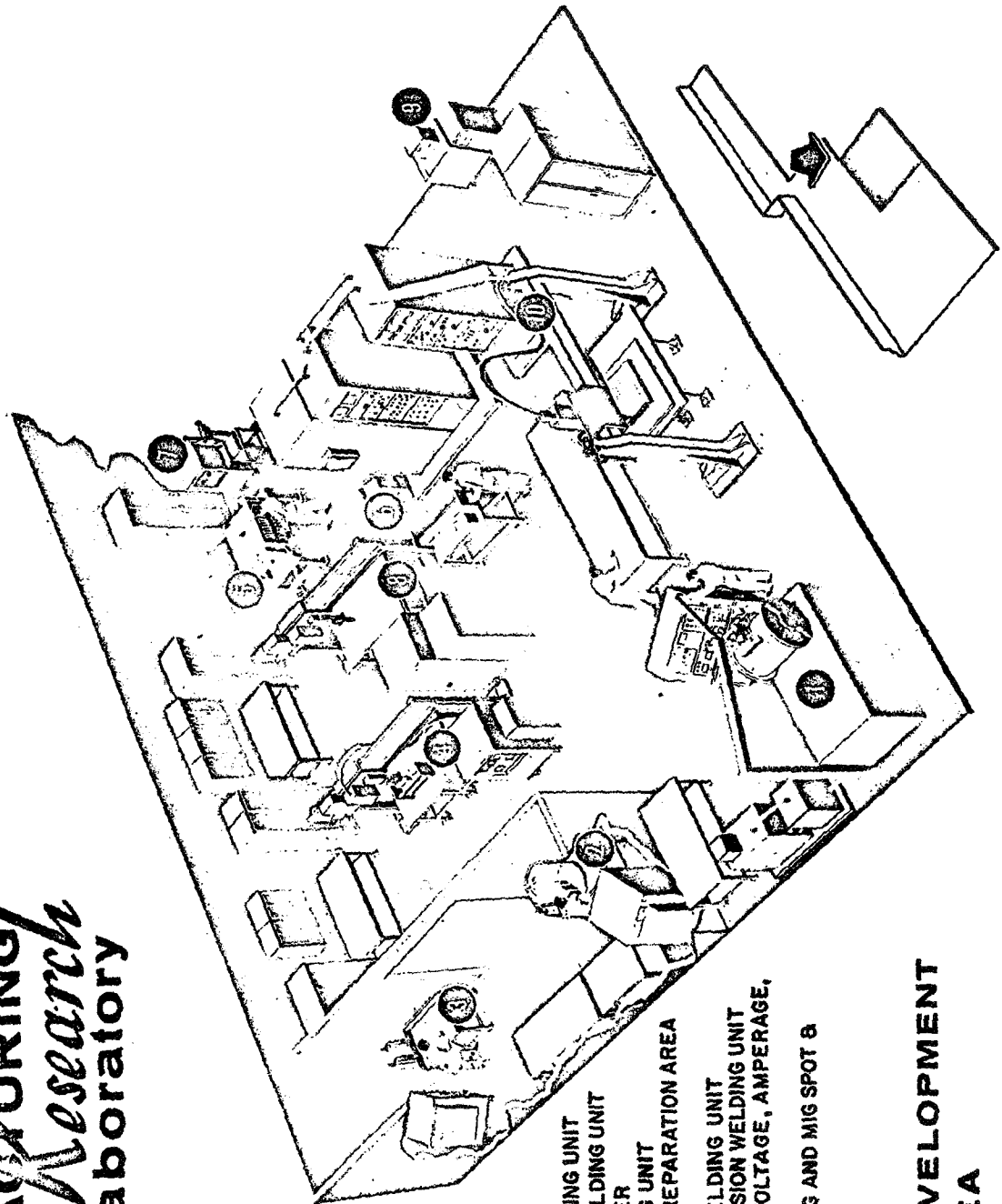
A) PENETRATION - CURRENT - PROXIMITY RELATIONSHIP



B) PROXIMITY CHARACTERISTICS

Figure 8. Power Source Static Characteristic Determination on the Basis of Experimental Welding Data

# MANUFACTURING *Research* laboratory



1. ELECTRON BEAM WELDING UNIT
2. PLASTIC CHAMBER WELDING UNIT
3. METALLIC ARC WELDER
4. BUTT FUSION WELDING UNIT
5. HONEYCOMB BRAZE PREPARATION AREA
6. TACK SPOT WELDER
7. VICKERS TIG SPOT WELDING UNIT
8. SCIAKY TIG SPOT & FUSION WELDING UNIT
9. RECORDING EQUIPT. (VOLTAGE, AMPERAGE, PRESSURE, TIME)
10. SCIAKY INTEGRATED TIG AND MIG SPOT & FUSION WELDING UNIT

**WELDING DEVELOPMENT  
AREA**

## DISCUSSION

Mr. Jackson: This is the first talk we've had on arc characteristics and power sources in this session. I think we have another series of questions coming up. Do we have a question coming up? Here's one right here. Matt Waite?

Mr. Waite: If I understood correctly, in your very interesting paper, Mr. Goldstein, you showed where the wire feed was kept constant, the travel speed was kept constant, and the gap in the joint to be filled was varied. I'm wondering just how this would all tie together because if the travel speed and wire feed were constant there would only be a fixed amount of filler.

Mr. Goldstein: The proximity was kept constant; the distance between tungsten and the work base was constant; the travel speed was kept constant, as you say; and the wire feed was kept constant---cold wire---this is tungsten (TIG) process. The change in arc length was due to change in the weld crater size itself---the depth of the crater into the workpiece.

Mr. Waite: But if we had a situation wherein you needed a  $\frac{1}{2}$  square inch cross section filled and a different situation where you needed a full square inch of cross section filled, with constant wire and travel speed you would only get a half square inch of cross section for the big fill and there would not be enough there to fill it.

Mr. Goldstein: Yes, sir. You are correct to that point. This is theoretically how it would work. The point of this was to show that we could get constant penetration. Now if we were also concerned with the reinforcement on top, perhaps we could use some other device to control the wire feed speed.

Mr. Chyle: Jack, I think you are on the right track as far as power source characteristics are concerned. We have seen similar results that you spoke about. Your one illustration where you had variable heat sink was an interesting one, because where you had it narrow, the current went down. I looked at that as possibly a change in the resistance of your circuit, and that the effect on voltage is such that it changes the amperes at the same time. I think preheating does the same thing. If you leave everything the same and just run a bead on solid plate, simplified, you'll find, too, that the current changes with no physical changes, whether it's hot or cold. And again, it has a relationship, I believe, in the total resistance of the circuit. But all in all, with the work that is being done in this area, I'd say there's hope for getting a power source of the kind that you want. I don't think it is available, off the shelf, but I think there's work being done in that area so that it will be self-compensating for the thing that you are striving for. I can say that the work we have done does parallel with your thinking.



Mr. Goldstein: The only piece of equipment we need right' now is one that will give any power source characteristic that we may so choose. And we have worked out a black box device that we'll be trying at the end of this month to just attach to any power source that will be able to do this.

Mr. Schwinghamer: I might have cut the feature here, I don't know, but what material were you using: Was it aluminum?

Mr. Goldstein: In every case, except the last instance, it was aluminum.

Mr. Schwinghamer: And what shielding gas?

Mr. Goldstein: I believe we were using Argon.

Mr. Schwinghamer: Well, you see the question I really wanted to ask was what would you observe with regard to those characteristic curves if you started to switch gas mixture, especially with regard to the puddle or the crater depth?

Mr. Goldstein: Oh! The arc characteristic curves? Well, certainly the arc characteristic curves would change. I think that Jones of Johns Hopkins has published a great deal about it---the effect of gas atmosphere around the arc.

Mr. Schwinghamer: The point is, there would be some degree of effect in sensitivity, I think, wouldn't there?

Mr. Goldstein: Yes.

Mr. Schwinghamer: It's going to radically effect the sensitivity. Suppose you ran a 100 percent Helium. This changes the crater depth consideration entirely.

Mr. Goldstein: Yes, this question is well taken. This is the beginning. All this has to be worked out and felt along with. The sensitivity would change.

Mr. Bandelin: I agree with Mr. Chyle. I think you are absolutely in the right direction, and we need this very badly. However, have you considered the effects of the type of work that you are doing on the relationship of mismatch; do you think that you will be able to control this with the complete penetration, also?

Mr. Goldstein: Yes, actually this is one of the problems in development, to find out what particular characteristic you have to have to get equivalent heat sinks. This is part of the development, and we think we could do it. Now, there might be one additional requirement for mismatch. And that is to change the location of the tungsten relative to the joint. This would not do that. This would only change the power input to the joint. We are going in that direction of study.

Mr. Jackson: Can we have one more?

Mr. Gaw: I would like to ask the question. Were you casting to a backing bar, or was the gap freely unsupported in space and your weld puddle allowed to form between the two plates and retain its position by capillary action?

Mr. Goldstein: Well, that first illustration was theoretical. The case of the variable speed and the scallops situation was just a bead on plate.

Mr. Gaw: Okay. For the situation that you have described, I get the impression that you are detecting the change in distance between the tungsten and the molten surface as a result of the weld puddle dropping from the tungsten and creating a voltage change across the arc.

Mr. Goldstein: Almost. We are detecting a change in the arc characteristic which is more than just a voltage change.

Mr. Gaw: The way you have drawn up your power supply curve, that's true, but effectively you're altering your arc length; isn't that true?

Mr. Goldstein: Yes, effectively we are changing the arc length, but the point is, that when we change the arc length, we are doing more than just changing the voltage.

Mr. Gaw: Sure, you are. With your power supply, you're actually designing a servo system that is very effective.

Mr. Goldstein: The point is, the servo system already exists with the ordinary welding circuit. We're just trying to exploit it.

Mr. Gaw: Have you established yet that this servo system is effective in doing what you want it to do at all?

Mr. Goldstein: No, not yet.

Mr. Hackman: I'd like to predict, if I can, your first situation is not even a question. I think it's a fact. In other words, I think you are going to be quite successful with the drooping characteristic of the CP type power supplies---any that lie in this region. However, in the other case of the rising characteristic, the positive resistance will exceed the characteristic of the arc. I think you may be headed for an unstable condition because this is the same situation that would occur if you were to take a rising characteristic power supply and eliminate the power cable that it was designed to operate with, the manual torch. If you get rid of this resistance here and substitute a mechanized head, you will find that as the demand for voltage, or as your system sees more voltage, the power supply will deliver more and it will chase itself right on up the line. In other words, in this area I think you may have difficulty, but I think in the first area, you are definitely on the right track.

Mr. Goldstein: I think the problem of the stability of the arc really depends upon the relative slope of both the power source characteristic and the arc characteristic. We are also exploring what happens when these two characteristics are nearly parallel to each other. We haven't done that yet. But if they are perpendicular to each other, or if they make an angle, an acute angle with one another, I don't see why the arc should be unstable. I just didn't follow your reasoning of why it was an unstable condition when we have a rising characteristic.

Mr. Hackman: This is true when the power supply is drooping. The more angle you have between the two, the greater the stability. As they approach each other, the stability decreases. And in effect, as they cross over, they go into a region of complete instability. This is what I think will reappear in the latter case.

Mr. Jackson: Woody, this looks like you're going to have a lot of fun in the months ahead in order to provide us with a session for the next meeting that we have with gear and equipment and everything on it. Well, thank you a lot, Woody, and I'm going to turn the meeting back to Jim.

TORCH GUIDANCE USING CLOSED CIRCUIT TV

By

A. T. TAYLOR

THE BOEING COMPANY  
SEATTLE, WASHINGTON

## INTRODUCTION

In these few minutes I intend to describe a simple method of applying CCTV to the general problem of torch guidance. I believe that the need for torch guidance is accepted and I will say only a few words on that subject.

### Torch Guidance System

The principal justification for using a torch guidance system is the cost savings which can be obtained if we can hold large details in a tooling system that does not rely on absolute pre-positioning of the details. Slight movements of the joint, due perhaps to expansion or contraction stresses, can be allowed. Structurally simpler tooling is possible since the operator would not have to accompany the torch. Therefore, there is a need in specific cases for the operator to view and command the arc position from a distance.

Comparative methods of torch guidance were examined briefly. Automatic seam tracking devices that will handle a variety of situations with high reliability are not yet completely operational. A system of mirrors and lenses which would project an enlarged image on a frosted screen was rejected as well as a system of mirrors and a binocular or telescope. Fiber optics were considered. All of the above systems except CCTV were considered to have limitations as to the distance and direction from the arc that they would be serviceable.

### CCTV

CCTV is regarded as the best possibility. In addition, it has the novel feature that it is possible to record the picture on tape. The possibility of comparing the radiographic record of the weld with the arc action is attractive.

We are aware that other companies have also made use of CCTV. Lockheed, Westinghouse, and Bendix have used or use systems identical in many respects to that developed at Boeing. We believe, however, that we have some useful refinements.

The basic problem with the use of CCTV is excessive contrast of the arc with the surroundings. The ratio of light intensities between the arc and surrounding area is of the order of 10,000 to one. Direct exposure of the TV camera vidicon tube to such large light intensity would irreparably damage the tube, and obviously a filtering system is necessary. Blanket filters, however, reduce the overall light level to such a degree that the background areas away from the arc proper cannot be adequately viewed. The use of a No. 4 welder's filter is an example of this approach.

The solution appears to be one of intercepting and filtering only the rays of light from the arc and allowing the reflected light from the surrounding area to reach the camera tube directly. The original method selected by Boeing to do this is with gradient density filters in combination with spectral filters.

Gradient density or spot filters are those where the transmission factor varies from point to point over the surface area of the filter. The spot filter we employed was made from a photographic negative obtained on a special set-up. This is shown in Figure 1. A piece of white paper represents the arc. The area in front of the white arc spot was shaded from white to dead black to subdue some of the bright reflections near the puddle. The film was loaded into a slide holder and mounted at the image plane of the lens system. The lamps were adjusted to provide specific and general illumination. By trial and error, a procedure was developed that produced an acceptable filter. Essentially, this was as follows:

1. The film we used was Gevart D-2 single emulsion which is a slow speed, fine grain film.
2. This was exposed for 20 seconds at F16 using general light only and exposed again for 1/20th second at F16 with the arc illuminating spot light on.
3. The film was developed and re-inserted in the film slot of the lens system.

The spot filter was placed within the lens system again at the image plane. In actual use a secondary system of polaroid filters, color filters and an automatic diaphragm to prevent damage to the vidicon tube was included. In later systems the spot was placed within the lens system so that the aperture stop of the normal lens could be used to control the spot diameter. Rotating the diaphragm stop ring varies the spot diameter. A schematic of this system is shown in Figure 2.

Using this arrangement during GTA welding, it was found that the tungsten electrode, the weld joint, the wire melting into the puddle, and even soot blown by the shielding gas could be seen. Figures 3, 4, and 5 indicate what could be seen. In these photos, although the wire, arc, and surrounding area can be pointed out, considerably more detail can be seen by viewing the monitor by eye.

The torch position relative to the joint was adjusted by the cross seam positioner which contains a reversible motor. The motor was controlled by a double throw toggle switch.

Our studies have found that CCTV can be successfully applied. A compact camera weighing less than 5 pounds with automatic 4000:1 light ratio compensation has been selected for further work with the lens system. We believe that a relatively sophisticated system is possible and we are progressing in this direction.

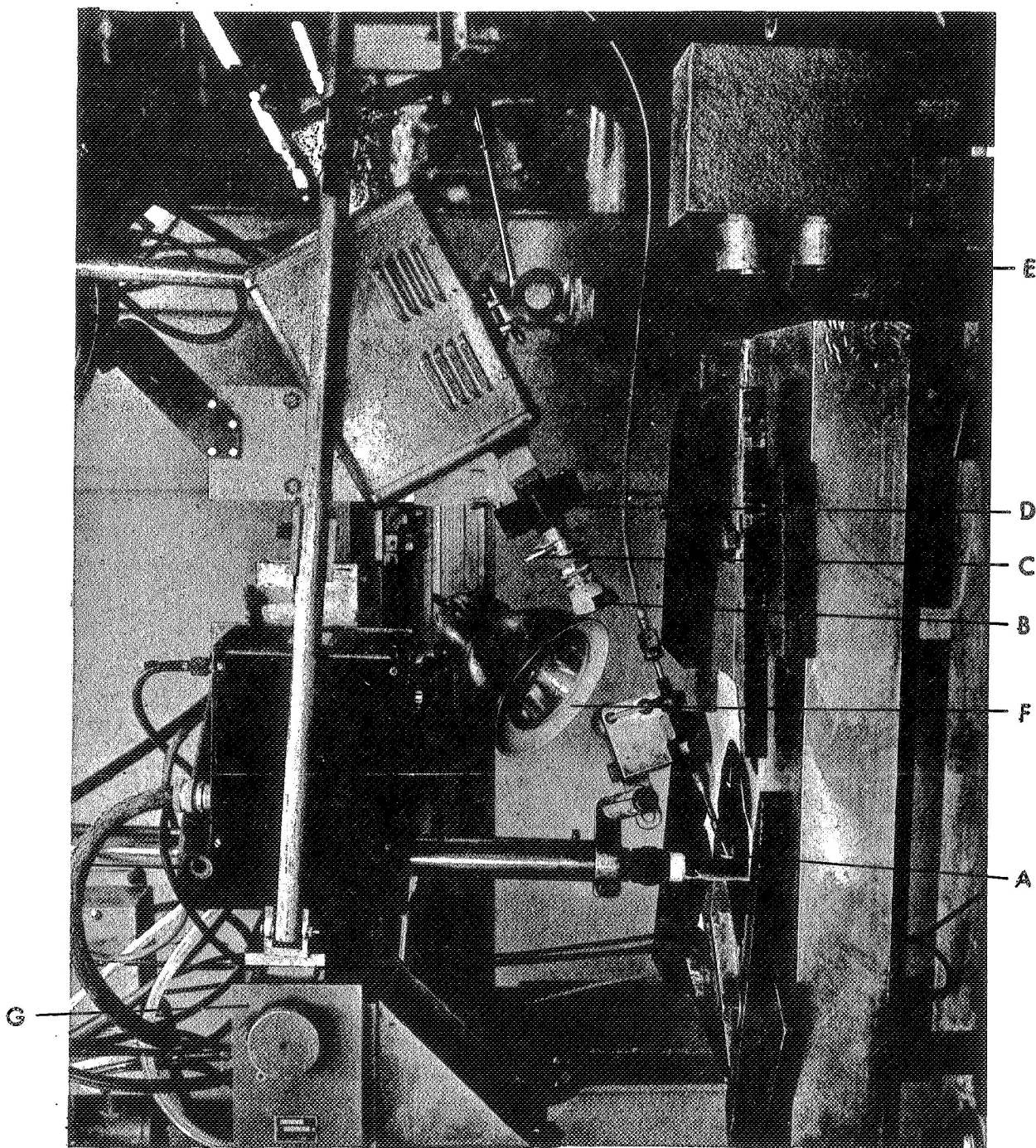


Figure 1. Special Set-up for Obtaining a Spot Filter From a Photographic Negative

- A White Spot Substituting for Arc During Exposure of Film
- B Shutter Attached to Front of Camera Lens
- C Film Holder Located at Image Plane of Objective
- D Automatic Diaphragm Safety Device
- E Lamp to Illuminate A During Film Exposure
- F Lamp to Illuminate Subject During Set Up
- G Cross Seam Positioner

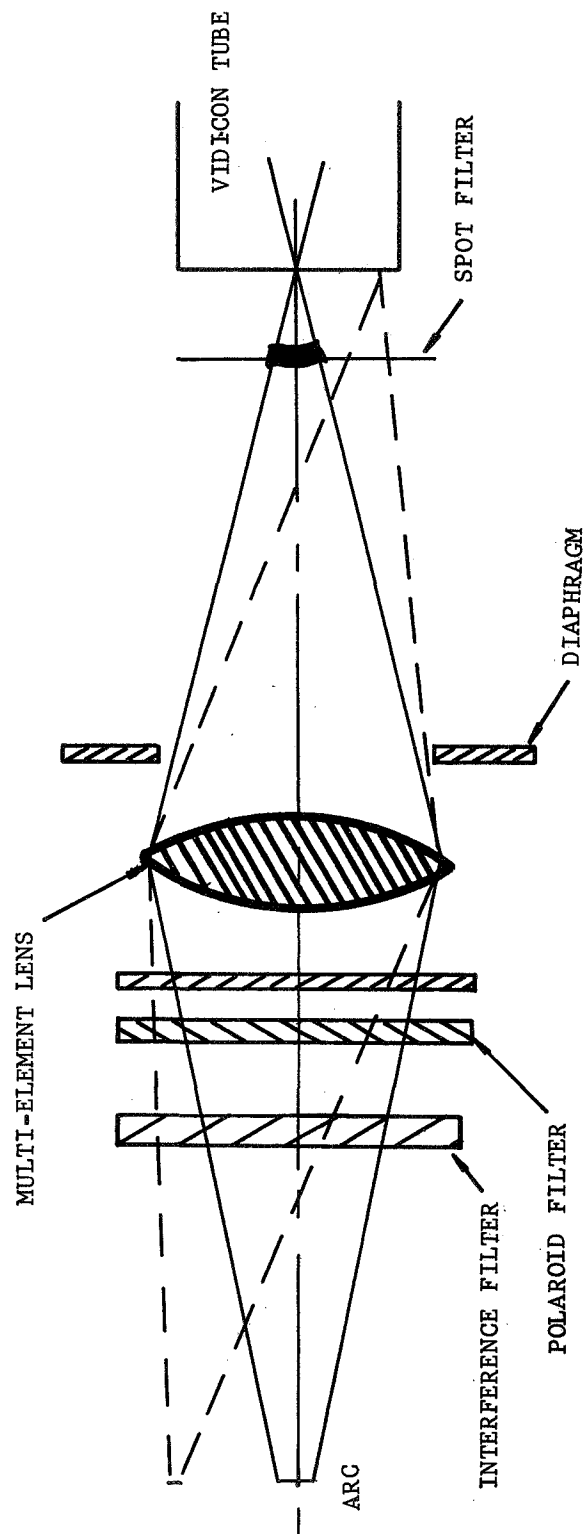


Figure 2. Schematic of Lens System CCTV Torch Guidance



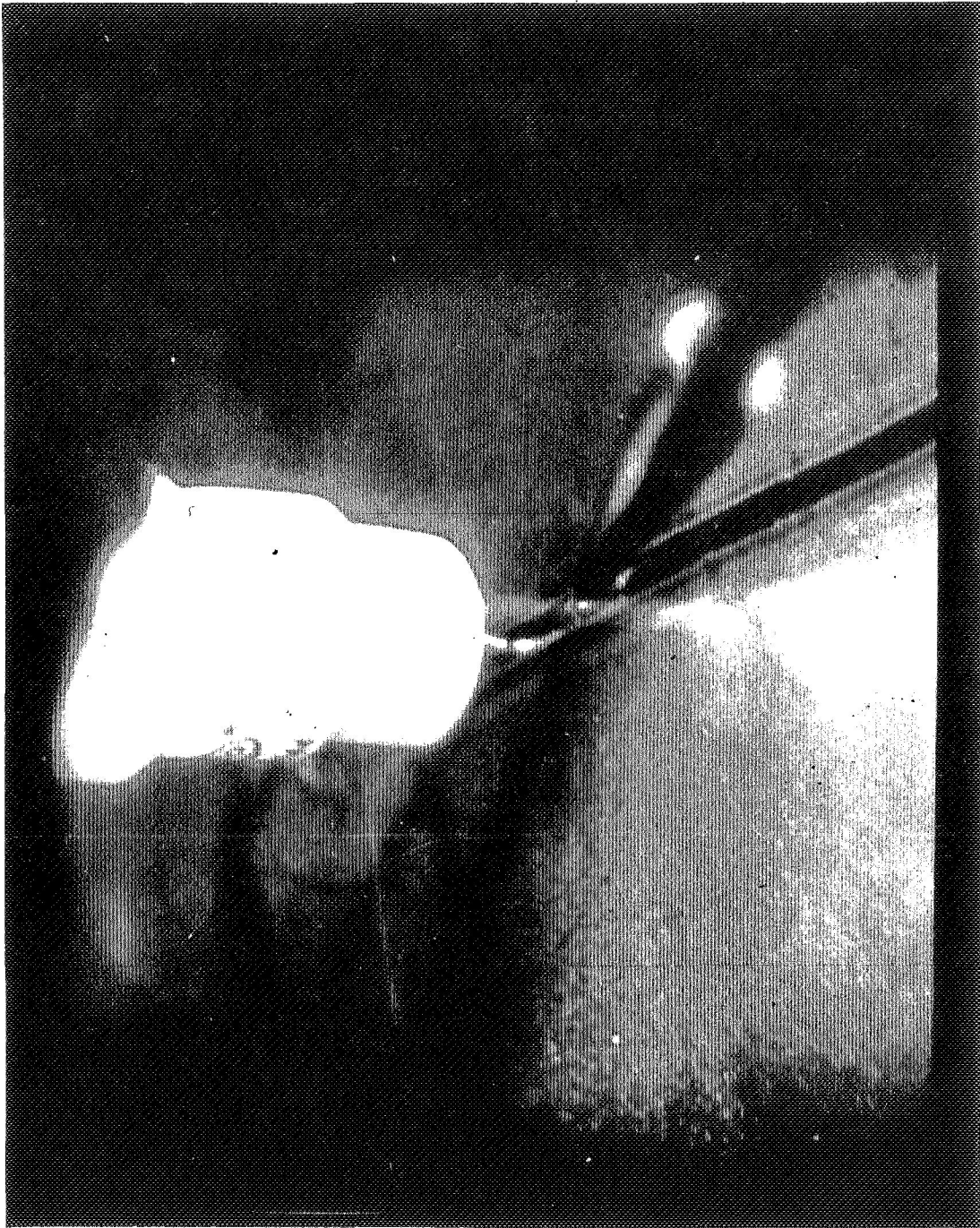


Figure 3. Typical Vision With The Arc Off, Not Welding



Figure 4. Weld In-Progress. Filters Adjusted to Dense to Demonstrate Ability to Mask Out The Arc Completely if Desired. Diameter of Masked or Filtered Spot is Readily Changed by an Iris Diaphragm.

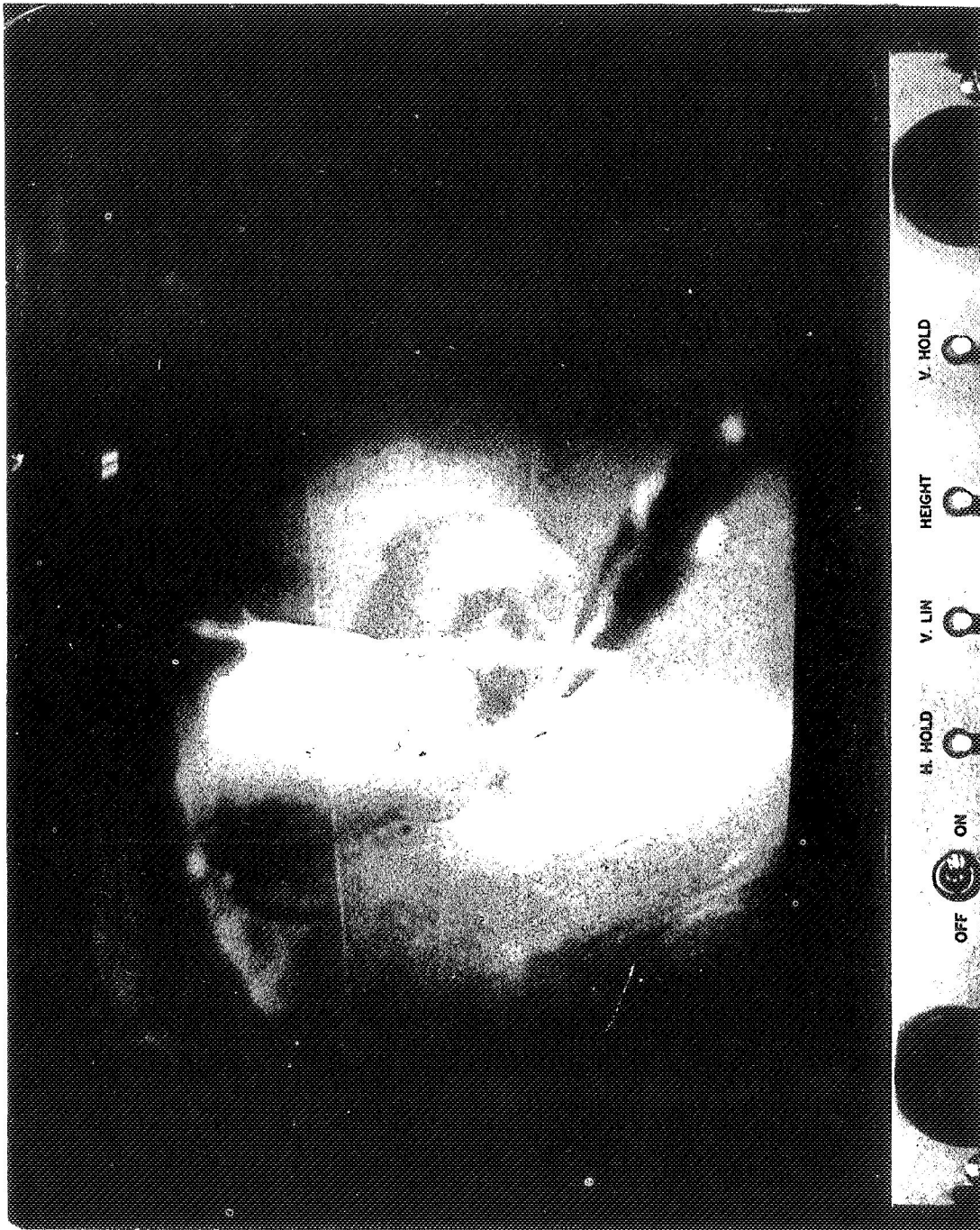


Figure 5. Weld In-Progress. TV Screen Not Adjusted for Greatest Contrast

## DISCUSSION

Mr. Kelker: That was a very interesting paper, but I am sure you also have a lot of questions regarding this type of subject. Does someone want to open the questioning? All right, I'll open the questioning, since I can get a little bit closer than you can. I'd like to ask how the television is affected by strays and by transients.

Mr. Taylor: We have observed no problem in this. It's clear as a bell, as clear as you can make this kind of an operation. The biggest problem is really the welding on aluminum surface. There is a tendency for reflection. You must play with contrasts and get some of it out. It's relatively straight forward. I don't think there is anything particularly unusual about it. I am sure any of you could apply it to your operations if you have the need.

Question: I am very interested in the puddle activity. Do you think that you could use this camera technique to study the puddle activity?

Mr. Taylor: I watched many of these being made, and you could see what is called the "mackerel" motion of the puddle, you know, surface jittering, etc. If that is what you're looking for, I don't see why not. You can focus right in on the puddle pretty accurately. The magnifier---local area magnification type thing---as long as you have enough lines of resolution, moves right up and you can see quite a bit.

Mr. Seaman: You mentioned the \$3,500 cost, and you noted that this was the system cost. Could you describe what was included or whether you had other costs for special lens systems beyond this, or other engineering costs?

Mr. Taylor: Here's the way it was presented. We can rent this system for about \$250 a week. This is the way that we at Boeing would probably do it, the reason being that we don't have people who could maintain and service CCTV system. So, for our type of stuff, we would probably go out and rent it. They said that the individual Sylvania 800 camera was worth about \$800. And they just said the complete system, I presume that this is the camera, the camera control monitor, and the TV screen. I think when you buy that, you've got the package, and you've got the problems.

Mr. Seaman: You mentioned services. Has this been a major expenditure?

Mr. Taylor: No, not particularly. In fact, I don't know of any service they have had. In some cases, they wanted to change this or that, and again, we don't have people that are experts in TV.

Mr. Gaw: I wonder if this system includes provision for moving the focal point of the camera from place to place while the weld is in progress?

Mr. Taylor: The system I had does not. We have a more sophisticated system design being built that does. Yes, you can zero in on just about anything you want at that point.

Mr. Gaw: Does that system also include a camera positioning device?

Mr. Taylor: Yes.

Mr. Gaw: Is there some sort of estimate you could tack onto the cost for that system?

Mr. Taylor: No.

Mr. Kelker: Are there any more questions, gentlemen?

Question: Let me add another question to the question I had about puddle action. I would like to ask specifically about the arc image itself. I hate to use the term the 'plasma' because I'm not sure that's what we're looking at, but what the welder calls the plasma. Can you see this pretty well?

Mr. Taylor: I don't know quite how to describe it. You can adjust the spot filter so that you get a big black spot, and you can cut out the arc entirely and intensify that background effectively. Otherwise, you can cut down the background and bring up the arc area, I'll call it, until it dominates the picture. Now, as far as seeing the arc, and being able to learn anything about it, I would be a little doubtful about it.

Question: Can you see the welding action?

Mr. Taylor: Yes. You see the wire coming in and the joint kind of sweeping below you, and you see the marks on the surface of the plate. Well, the plate did not move in our tests, the torch did---and so all of this is quite well under control. You can get an impression, we have never tried to scale, but I think you could, of the proximity of the cup to the work. Anything like this you can observe, and as I say, you can see the soot kind of blowing around the edges; so, in that sense, it's pretty valuable.

Mr. Kelker: Well, we are running out of time. Thank you, Mr. Taylor.

EQUIPMENT PRECAUTIONS ESSENTIAL FOR  
HIGH QUALITY WELDS IN THICK ALUMINUM

By

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## INTRODUCTION

Scientific advances in the aerospace fields have imposed many new and demanding requirements of exacting operations for translation of engineering criteria into space flight components.

Because of these requirements General Dynamics/Astronautics initiated a study to keep pace with the requirements of the advancing technology in the welding area. Fusion weld quality is a matter of reliably maintaining good weld schedule parameters in addition to preventing unnecessary contamination. Consistently high quality welds in thick aluminum present so great a challenge that it is mandatory to ensure that there is no aggravation caused by variables in the welding equipment itself.

We, like most other people, found that we could produce Class I welding to ABMA standards in laboratory controlled specimens two feet long. However, when it came to production length welds we broke our "pick". At this point it became necessary to analyze the problems and clean up those that we had control over. We believed the areas to concentrate on were:

1. Welding equipment
2. Welding procedures
3. Contamination control
  - a. Clean room environment
  - b. Gases
  - c. Filler materials
  - d. Plate preparation

This paper details the precautions observed in a recently concluded project to produce high quality weldments in thick aluminum alloys. Also included are comments about the precautions to an even, more effective degree. The project referred to was accomplished on two alloys, 2014 and 2219 in thicknesses ranging from 1/4 to 1-1/2 inches; in three welding positions, flat, vertical, and horizontal; and by two processes, TIG and MIG.

As stated in this study "water clear" welds were consistently obtained in test specimens. If I may at this time, I would like to say that the term "water clear" is a misnomer but is widely used. In this case, it means Class I ABMA.

## EQUIPMENT AND PARAMETERS

### Welding Equipment

Welding equipment used was of the most advanced type. It was specifically purchased for this project because the common types of equipment were generally incapable of the degree of control necessary.



Such equipment is designed to prevent osmotic contamination of the shielding gases. Accordingly high purity regulators are required. These are built with teflon seals instead of rubber. Stainless steel is used for all metal parts for prevention of air infiltration at potential corrosion locations. Fittings are attached by welding instead of by threaded joints. With the purchase of the regulators a certification was received from the vendor showing the leak rate. The regulators were tested by the helium envelope technique with a mass spectrometer. Certifications showed a leak rate of only  $9.2 \times 10^{-10}$  atmospheric cc per second of helium. This approximates one cubic foot in a hundred years. Osmotic contamination is also controlled by use of metal hose, better known as "wrinkle belly" stainless preferably, but copper or brass will do the job. Where it is impossible to use metal hose, the choice should be saran plastic. Although butyle rubber is slightly better than saran it is very susceptible to ozone deterioration. All internal piping in the welding machine should be metal with solid joints. To illustrate a problem, we received delivery on a welding power source that had all the obvious precautions for elimination of contamination of the gases built in. Upon using the equipment and checking out the dew point, it was impossible to obtain better than a  $-30^{\circ}$  dew point at the torch. On investigation it was found that the manufacturer had made his internal piping of tygon plastic tubing. Upon replacement with metal hose, we regained a satisfactory dew point ( $-65^{\circ}$ ).

Gas solenoid shut-off valves should not be more than two or three feet from the torch. In keeping this distance short, line contamination and purge time are kept to a minimum. For better gas coverage shielding of the weld puddle it is recommended that the large 500 amp gas lens torch be used. For those who wish to use higher amperage it is possible to go to 700 amps by simply water cooling a metal nozzle and increasing the water supply to approximately twice that recommended. In the torch there are several things that should be considered, some of which are usually over-looked.

1. Finish of tungsten (should always be same micro finish).
2. Is it of good quality (cracked)?
3. Is the configuration always the same?

These items should be controlled as they do have a significant influence on the arc.

### Welding Parameters

Weld quality is a matter of reliably maintaining good weld schedule parameters in addition to preventing unnecessary contamination that is within control of the process. Maintaining these parameters depends upon sensitive controls to correct for transient conditions.

Advanced equipment involved controls that go a long way in rapidly correcting for primary and secondary variations, but is total correction fast enough for any given weld? Since primary variations are taken care of by correcting the secondary it would seem conceivable that primary correction should be accomplished outside of the welding transformer thus



eliminating one more variable. There are various methods for check-out of the parameters. We at General Dynamics/Astronautics prefer a Brush type recorder. For the services, wire drive oscillation, carriage, and any motor function check-out is effectively achieved by tachometer generator.

The demand and cost of maximum quality and high reliability requires in-process monitoring of the process. For this purpose, high speed, very sensitive recorders need to be used for read-out of the major weld parameters, amperage voltage, carriage speed, wire feed, and oscillation. This should include a tachometer generator pick-up for the wire itself to check for any wire drive roll slippage. The Offner six-channel recorder is one such suitable instrument. It is capable of recording 500 cycles per second. With recording equipment with high response it is possible to pick up trouble in its early stages before it can become a source of problems. Whereas slower types do not indicate until the problem has become acute.

## MATERIAL CONTAMINATION

### Gases

It is also recommended that all gases used be certified by your own laboratories, not only for oxygen but also for other impurities which have a great influence on the arc stability. For the most part we use an Alnor instrument for checking dew point, but for the more sensitive work a cup dew pointer is used. It is also used to periodically check the Alnor.

### Filler Wires

Filler wire of high quality is also a must. Our work has utilized both the missile pack and the HQ canned wire. Both have left higher quality to be desired. The noticeable metallurgical defects that were observed were coring and a contaminated oxide surface. The coring is a factor that the user can do little about except to pay a premium for sonic inspection and hope that it has eliminated the possibility of receiving bad material. Oxide on the surface can be minimized by:

1. Not breaking the seal until time of actual use.
2. Atmospheric control cabinets for storage.
3. Continuous purging of the filler wire reel case, approximately two cu/ft per hour.
4. Precleaning of wire at the time of use, just before entering the weld puddle.

As for precleaning at the time of the welding, we at General Dynamics/Astronautics feel that a solution has been found. No matter what the surface oxide may be, it will always be removed and the wire will enter the weld puddle at the same level of cleanliness. Details of this will be discussed later.

## BASE MATERIAL

Conditions of material to be welded are and have always been a major factor in the final quality of the weld. To date, the best procedure of preparing the joint area has been a mechanical removal of metal. This is accomplished by either machining or hand scraping the joint just prior to welding. Hand scraping can normally be accomplished immediately prior to welding. A recently conducted program at General Dynamics/Astronautics has shown that there is a distinct change in the quality of fusion welds relative to the chemical cleaners used. Two cleaners used in a comparison were commercially available aluminum deoxidizers. Welds made without scraping averaged 7.0 percent defective for one of the chemical solutions and 11.5 percent for the other. Welds that were made on hand scraped plates showed less than 1 percent defective welds for each solution.

## RECOMMENDATIONS

Although the best of today's equipment is an improvement over pre-space era equipment, there is still a lot to be desired as it still does not incorporate all the control that is needed. For example, it is felt that voltage signals from the MIG contact tube are inadequate; that a more positive system is needed. To this end we modified a standard torch so that brush pick-up is obtained from the wire at a point just above the contact tube. Another area is the contact tube as a current carrying device. Some better method is needed. Much work has been done to develop a better means, such as liquid metal. But to date, this has proved to have more handicaps than advantages. Still another area that is in real need of improvement concerns oxide free filler wire. Of all the various in-process cleaning techniques available one potential, as previously mentioned, appeals to us. This potential is cathodic cleaning. This is accomplished in a small chamber surrounding the wire just ahead of the torch or cold wire input. This chamber rotates around the wire which is being fed through the chamber. Rotation is approximately 2,000 to 10,000 RPM depending on the wire being cleaned. A very low voltage and amperage are established between the wire and an electrode in one wall of the chamber to effect deoxidation in an inert atmosphere. We have developed a compact system including a power supply, and it is in the final stage of completion. The pictures I have here are of a "bread-board" bench model that is currently in use for cleaning stick lengths for manual welding. (See Figures 1 and 2)

## PLANNED PROJECTS

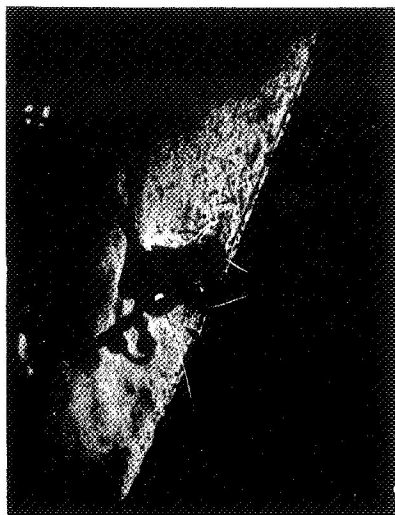
Some programs for improving our welding capabilities are currently in the planning stage. Two of these that we are particularly interested in are:

1. Development of an aluminum deoxidizer which precludes scraping plates prior to welding.
2. Use of infra-red technique to detect penetration and porosity as it occurs during welding.

The development of cleaning solutions may sound presumptuous. However, our chemists have recently developed new solutions for cleaning of maraging steels and are presently working with solutions for maglithium alloys.



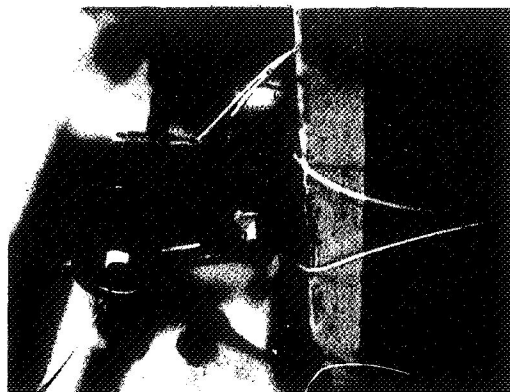
General set up showing  
power supply, wire  
feeder and chamber



Chamber in  
operation



Close up of  
Chamber

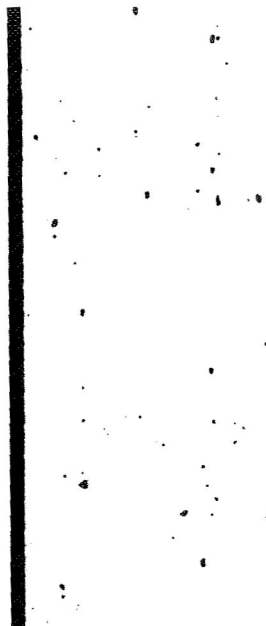


Close up of  
chamber-net  
operating

Figure 1, Cathodic Arc Cleaning



As received - transverse section showing non-metallic inclusions  
MAG: 200X  
Unetched



As received - longitudinal section  
MAG: 200X  
Unetched



Cathodic arc cleaned  
As received  
MAG: 4X



As received  
Cathodic arc cleaned  
MAG: 1X



Cathodic arc cleaned  
As received  
MAG: 4X

Aluminum Filler 2319

Figure 2. Filler Wires

## SUMMARY

In summary we can say that to assure quality welds in thick aluminum the following items are essential:

1. Welding equipment must have self contained contamination control.
2. Weld schedule parameters must be closely and precisely controlled.
3. Gases, filler wires, and base material must be subjected to severe quality control procedures.
4. Future work must be initiated and carried through for improving equipment, weld schedules, material preparation, and surveillance.

## DISCUSSION

Mr. Kelker: Don't go away, Bob. You've made quite a few controversial statements, and I am sure there are going to be a few questions. Now, don't all of you put your hands up at once; we'll get to everyone of you. Who wants to start it? The gentleman in the back; your name, please.

Mr. Martin: Just exactly what mechanism cleans this wire? Is it an abrasive action, an air blast, or what accomplishes the wire cleaning?

Mr. Manary: It's a deplating operation; it's actually removing metal. This work was all done with reverse polarity. I might emphasize the reason we used reverse polarity---well, you know the reasons for this, but the lower amperage is a must at this point. You have to establish a large enough electrode so that you're not spitting tungsten and adding to your problems. We use a large electrode and keep the amperage down pretty low. Actually, it deplates. I think that Marshall down here has one of our movies that was made of the MIG process, which is a reverse polarity process. It shows very well this deplating happening---the oxides coming off. I started working on this thing in about '54 with the B-52's. Any of you fellows that work with the 502 rod know what a sticker is. Especially coil wire where it continually rusts. We had to find a way to get rid of this rust. So, I worked with wire brushes, a little bit of everything, and I started developing this thing at home. But after buying the first tank of Argon out of my own pocket, I said to heck with it. Let the company pay for it. So now, that's where it is. But depending upon process, which I found out, this equally cleans titanium wires and steel wires. You can use high frequency by itself, depending upon what you're doing and the size of your wire. You can use high frequency with DC or high frequency with AC. The power supply that we built is made to do this. Actually, it was only educated guessing. We didn't know what the devil all the problems were going to be, so we built a power supply that we thought would take care of most of them.

Mr. Platt: Two questions: one, what type of surface finish do you get on your wire when it comes out of your unit? Second, since you said this is a deplating operation, what happens to the small particles which are removed?

Mr. Manary: They are exhausted out the side as the gas escapes. The gas does carry this off. I was afraid you were going to ask about the surface because I know you've been fooling with this. Surface finish, to be truthful with you, I can't answer this question because I haven't measured it. We have looked at it up to 500 magnifications; it is rougher. It's a lot different after going through a swagging die and shaving than shaving and going through a swagging die. It's removed metal; so it's rough. Now, in the MIG process, this would give you a problem, but I'm not sure that you need this in the MIG process. In the MIG process, you get a good enough deoxidizing, I believe---this is only my own theory and I won't argue about it because I have no statistical data to prove this, and I don't think anybody has on the other side either---but I think that you actually deplate this wire good enough with the reverse polarity during the MIG

process, that you don't have to worry about the oxidation. The oxidation that you have to worry about is that which you haven't taken care of---already on the plate---from dirty handling and greasy hands. If this were used with the MIG process, then I think we have to take a very close look at the surface condition. But at this point, I haven't been too worried about it. I hope that answered your question.

Mr. Seay: Have you run tests to determine exactly what difference this makes as far as porosity, tensile values, and so forth.

Mr. Manary: Yes, we've run tests. This is a very elusive thing. This is like trying to put porosity in a piece of metal. If you don't want it, it's there; but if you want to put it in to a consistent result, it's real hard to do. In other words, I've run wire, as I said, on a laboratory basis, cleaning everything else up, out of a normal package that has been a year old---shelf-life a year old---and had no problem with it. But yet, tomorrow, I can have a problem. I am only saying that this is one thing we have done to clean up the process. We know we are going in with the same level of cleanliness all the time. I don't say that this is an answer to eliminating porosity. I'm saying that if I go in with the same level of cleanliness, I know where I stand. I don't know it's high today and low tomorrow. This is the same with your gases or the same with your tungstens. Whatever you do, control it; know your level of control. Get control of it, even if your control is bad, and you will know where you are. But if it is here today and there tomorrow, you will never nail down these things. It's just like hoses---I mean, I have preached gases for so long, I am blue in the face about it. But here a couple of years ago, or about four years ago, I had the opportunity to work on nuclear reactors---Zirconium. We had a problem. We had a liquid system; we couldn't get good gas. We were working in a dry box. I know some of you people say, "Ah, that's electron beam work," but we were doing it cheaper and just as good without electron beam. But we had a gas problem. We actually rebuilt a purification system ourselves to re-purify the liquid system that was in the plant. Now, the liquid at the system itself, let me clarify, was good; but by the time it got down through the piping in the plant and somebody opened up a valve for a couple of minutes and it sucked in some air and someone used it to blow off their bench or something, we got down to where the liquid was roughly a minus 25. And this is just not good enough to weld Zirconium. I'm trying to say that you should always know your level of cleanliness. I would like to know a way to check it. We have tried everything we can think of, and we don't know.

Mr. Stein: You used the term 'coring' in reference to welding wire, and I don't quite understand what you mean by coring.

Mr. Manary: Well, I don't really know whether it is coring or not, but it's inclusions in the metal. I guess this is possibly just some terminology that we boys use. We have found inclusions, possibly from the swedging operation after shaving, because they lie pretty close to the surface of the material. We have found inclusions in there as large as forty thousandths of an inch in length and about five thousandths in diameter. We call this coring.

Mr. Kelker: Gentlemen, we have time for just one more question.

Mr. Vilkas: Your comments with respect to welding were interesting. Would you repeat again the requirements for the power supply?

Mr. Manary: Do you mean the tolerances that they are presently built to by the major manufacturers? Well, usually they are made to compensate for a plus or minus 10 percent within 1 percent, and they are doing this by compensating on the secondary. Take Linde, for instance. They have a servo-drive mechanism that is doing this, and I know very well that this thing will not work within ten cycles. I am sure that the magnetic amplifier will not do it either, because I have checked them out with my recorders. As fast as they are, I know that they are telling me a true story.

Mr. Vilkas: Are you basically talking about TIG?

Mr. Manary: TIG or MIG, I don't care. I am saying, "Let's get a better power supply."

Mr. Vilkas: If you are talking MIG, you know that most people are using CP. Their reaction time has perhaps a different meaning.

Mr. Manary: Yes, but still your transformer does only what you put into it. I know this is a real hairy area to get into, and I just throw it out for thought because I am not positive of all my convictions. But I do believe that for the money that is being invested in a piece of welding equipment as you do a Pratt and Whitney jig bore, we ought to get something for it, instead of always saying that somebody must pay for the engineering, and this is what they tell us. I have stayed away from trade names, but let's throw it on the board. Believe me, I give Sciaky a lot of credit for one thing, if nothing else. At least they shook the hell out of the rest of the industry, and they made somebody else build some equipment!

Mr. Kelker: Thank you very much.



SIMPLICITY AND DEPENDABILITY IN WELDER  
CONTROL SYSTEMS

By

W.M. McCampbell

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R-ME-ME

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## INTRODUCTION

Welder controls, as a direct result of increasingly stringent requirements imposed by aero-space welding, have of necessity been developed to a high degree of precision. The increased precision has resulted in increased complexity and multiplicity of components, to the extent that reliability has become a formidable problem. This problem, with suggested partial solutions thereto, are the objects of this discussion.

Welding technology has advanced rapidly in recent years. It has possibly developed more rapidly than most of the manufacturing technologies. Control Engineering has played a vital part in this development. In fact, it appears that welding as a science rather than an art has placed more difficult tasks before the control engineer than it has practitioners of the other engineering skills. This is due in part to the fact that there exist broader gaps between the languages associated with the welding science than exist between those of, for instance, the tool engineer and the electrical engineer. The magnitude of the control engineer's problem has been related directly to the degree of precision required by the aero-space welding processes and to the extent that it has become necessary to rely less upon the physical skills of the craftsman. Electronics and related skills have been severely taxed to fill the gap.

Another factor has been the increasing size of the vehicle. The trend, due to higher tooling costs, has been to rely more and more upon precision controls in an attempt to offset those costs in time and money.

Let us look at a complete welding system of a few years ago. (See Figure 1.) In this system there is little more than a motor and a generator. The generator is special only in that it has an auxiliary series field which, on increased current, opposes the effect of the shunt field, resulting in a drooping volt-ampere characteristic.

It was simple, had few parts, and was physically almost indestructible. Except for the operator, who incidentally is still with us, this was the complete system. The operator had control of all functions other than current, including filler rate, travel speed, proximity, arc length, and seam tracking. Since it has become necessary to replace the stick electrode by MIG, TIG, and other processes, these functions normally can not be performed by the operator.

Now, in a typical aero-space fusion welding installation, most of the following functions may be subject to precision, automatic control:

1. Arc voltage
2. Weld current
3. Horizontal travel
4. Vertical travel
5. Torch attitude
6. Torch proximity
7. Seam tracking
8. and others

These may be compounded by programming of some of the variables, and, at best, due to necessity of interlocking the several functions, basic sequence controls are frequently very complex.

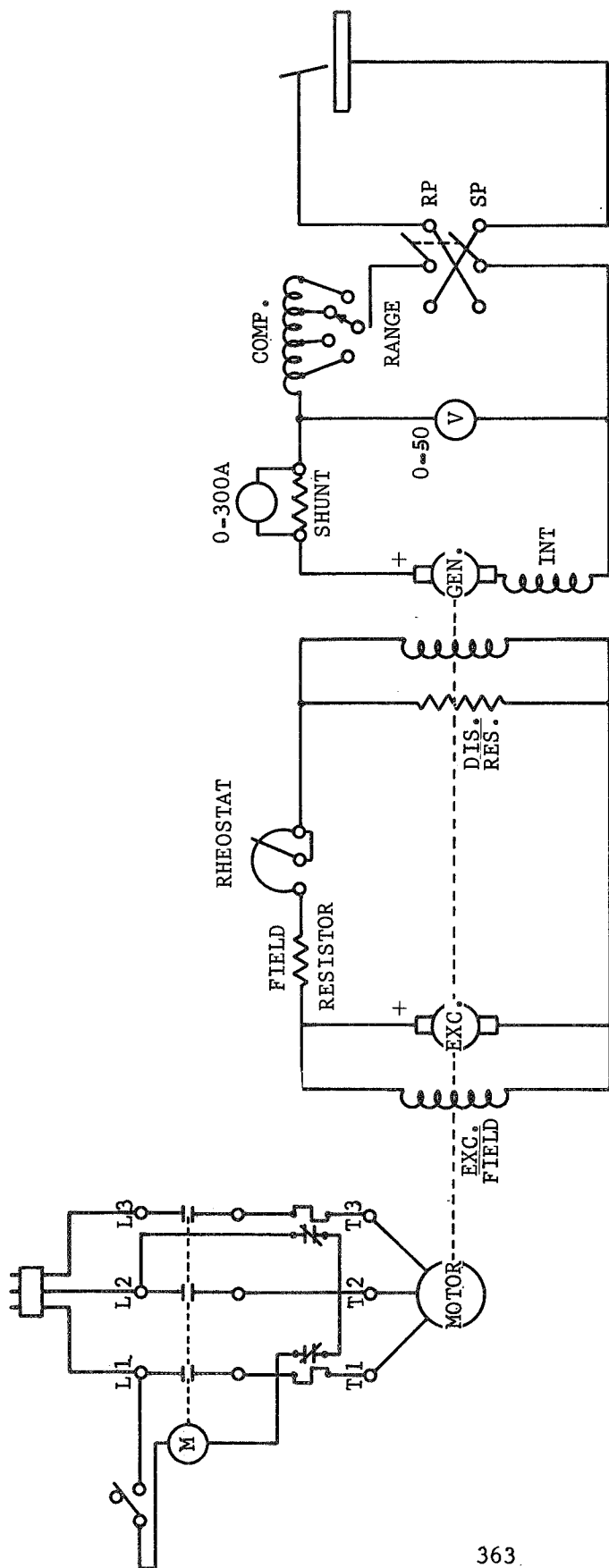


Figure 1. Elementary Diagram Typical Motor Generator Type Welder

By way of comparison with the complete system of a few years ago, look at Figure 2. This is an elementary diagram of only that equipment required to perform one function--namely, weld seam tracking. And this is not nearly complete, since each of the various blocks, triangles, etc., may represent a unit with more than a hundred basic components.

Filler rate and travel speed were first automated to some degree by use of a simple fly-ball governor--one basic component. This provided, at best, five percent speed regulation over a ten to one range. Later, electronic control became necessary, and required from twenty to thirty basic components. This provided speed regulation in the order of three percent of rated speed over a range of twenty to one. Presently, a typical wire feed controller may provide control accuracy well within less than one percent of set speed over a range of fifty to one, or better. But this is accomplished with one hundred eighty or more basic components. This may well represent better than a thousand percent improvement, at ten times the cost and ten times as many components. Power supply units, also, have experienced phenomenal improvement.

But a power supply unit, to maintain current within one ampere in three hundred, with extremely rapid response, must be sensitive to very small error signals. This requires higher impedance input circuits to servo amplifiers. Consequently it is, as are other controls, more subject to small extraneous signals. Recently, due to proximity of cables in two systems, a higher frequency start of the second system caused the other to lose the arc. This never happened in the older units with, typically, one hundred ohms input impedance, rather than 100,000, to the control circuit.

Certainly space welding can not be performed with 1950 vintage equipment and technology. But the many advances have not been accompanied by a relative increase in reliability. Equipment difficulties occur more frequently and result in much longer down time for each event.

It had been hoped that the use of semi-conductors would result in marked improvement in welder controls as it has in other areas. This has not happened. Actually, there is no way of knowing whether controls, with the necessary increases in precision and complexity, are more or less dependable than they would have been had designers continued to use the tried-and-true vacuum tubes, thyratrons, and magnetic amplifiers. But it is a surety that shop temperatures, shock, electrical accidents, and the old culprit, high frequency starting, take a heavier toll of the newer semiconductor devices than they did the old thyatron and the magnetic amplifier. Also, the typical semiconductor circuit has appreciably more components than the equivalent vacuum tube circuit. Consequently, in the Manufacturing Engineering Laboratory, when the choice exists on new equipment, there is now distinct preference for equipment utilizing the more conventional components.

It is often said that present day equipment is generally more sophisticated than the tasks require. In many cases this may be so. Yet an engineer trying to develop a method for performing a given welding task, needs the assurance that all controllable variables are steady. Otherwise he can not be sure whether any failure to meet objectives is the fault of the equipment or the method. With modern equipment, he usually has this assurance. Really, equipment has reached such a high degree of perfection with respect to resetability, accuracy, repeata-



bility, and response, that very little improvements can be made. Also, it is doubtful if any increased improvements would result in any improvement in the process. But too often, malfunction of equipment does become a problem. And with equipment so sophisticated that a one percent change in a sensitivity setting may make a vast difference in performances, the fine line between equipment malfunctions and misuse is often difficult to define, even with the best instrumentation available.

In this discussion, there have been several statements made, some of which may seem to be self-contradictory. Perhaps it would be well to summarize the pros and cons of modern welding apparatus. To the credit of modern equipment and its manufacturers, the following are obvious:

1. Equipment is vastly superior to that of even three years ago in capacity, precision, response, repeatability, resetability, and versatility.
2. Costs, though appreciably higher, are reasonable when compared with the associated advances in technology.
3. Such controls have undoubtedly made possible the use of the welding process for space vehicles using materials, configurations, and larger sizes presently incurred.

On the other side of the ledger, there are some deficiencies, which include these:

1. Equipment is complex and difficult to maintain. Designers have not always used tried-and-true-components and circuits to a reasonable extent.
2. The equipment is generally bulky, in spite of miniaturization of various subsystems and mechanical components.
3. Equipment, generally at the insistence of the user, has been designed for laboratory type welding, where welding in several modes may be desirable. Under shop conditions, the dependability of the system has been decreased by the existence of redundant circuits and features that may not be required for a particular application. Those may not of themselves be troublesome; yet when trouble does develop, they serve to confuse the issue.
4. Components are too often marginally rated. In a recently purchased system, 300 volt rectifiers were used almost exclusively. As these failed and have been gradually replaced by 600 volt rectifiers, incidence of trouble has been greatly reduced.
5. Miniaturization has been practiced almost indiscriminately. As an example, where a miniature motor is used where not absolutely necessary, dependability is not as high as if a more reliable, larger motor had been used.
6. Equipment has become more complicated to operate. The skilled operator is more of a necessity than ever.

7. The shop electrician, with his spare generator brushes and fuses, has of necessity been replaced by several technicians and engineers, with spare parts inventories that may cost thousands of dollars for a representative welding installation.
8. Too many long-lead-time special items, available from only one manufacturer, have been used.

In essence, as in other fields of endeavor, rapid progress in welding technology has brought with it many of the ills associated with automation and modernization. It is an apparent dilemma, but one to which there should be some solution--or, more likely, several partial solutions.

The first that comes to mind is that within the responsibility of the R&D personnel. This consists of choosing the better process for a given operation, with particular attention to selecting that process that is less subject to control problems under shop conditions.

Also, in the R&D area, regressive equipment available should be practiced. Certainly, the most precise equipment available should be used in the initial R&D effort. But in many cases, after a process and method have been established, a less sophisticated power supply unit, for instance, may be found, with little additional effort, to be more than satisfactory and possibly also a simpler voltage controller. This could result in the simplest practical system, with fewer redundant features, being placed in the hands of shop personnel, with less chance of failure.

Development of new methods may decrease the dependency upon sophisticated controls. One such method, in the early stages of investigation at MSFC and elsewhere, is series arc welding with independent control upon each torch. Techniques involving low heat arcs and periodic pulsing, high frequency resistance welding, etc., are being given consideration and are expected to be objects of study in the near future.

In these endeavors, the control engineer will undoubtedly play a major role. However, his best opportunities for immediate improvements lie in concentrated effort with known methods. In this respect, several possibilities come to mind. These include use of digital techniques, incremental servos; new devices such as printed circuit motors, AC silicon controlled switches, infra-red techniques, and others.

Areas in which the MSFC Manufacturing Engineering Laboratory is expending effort include the adaptation of digital techniques, in conjunction with more conventional analog techniques, to motor controls and arc voltage control servos. Another area in which rewarding work has been done is in the realm of utilizing temperature (or mass heat) sensing devices in order to develop a control more responsive to direct weld properties.



But in the rush to use new techniques and components, time-proven methods and components should not be forgotten, but rather reviewed in the light of present needs. In this way, often an old reliable tool can be used to perform a modern task. I would like to cite some examples.

Recently, in a MIG spot development program, due to a curious set of circumstances, including transistor troubles, it became necessary to provide voltage taper on a conventional magnetic amplifier power unit. The scheme adopted is shown in Figure 3. The taper control is nothing more than a conventional, simple, thyatron-type motor governor with an R-C circuit substituted for the normal speed control potentiometer. As the voltage in the grid circuit of the thyatron builds up exponentially, the governor tends to accelerate the motor so that the back-EMF of the motor is nearly equal to the voltage across the capacitor in the grid circuit. This is a relatively smooth DC voltage. Current is tapped off through a resistor and fed to the magnetic amplifier control circuit in such a manner as to oppose the effect of the regular control winding, resulting in a smooth, exponential taper of the welding voltage. Thus with simple, dependable components, a function was accomplished that normally requires much more sophisticated equipment.

Another problem that has apparently been reduced to simplicity is that of a low speed, low torque tachometer system to be used in instrumenting wire feed and in conjunction with friction drives where slippage may occur. Representative speeds to be measured are in the order of as low as three inches per minute, which on a one-inch diameter friction wheel, represents less than one RPM of a tachometer generator, well below its useful range.

#### Step-Up Gearing Requires Too Much Torque.

One system discarded rather early involved a very complex digital system which used a rotary pulse generator which alone costs more than \$2000. Another system would have employed Synchro transformers in conjunction with a conventional servo system. (See Figure 4.) In this system, the servo system acted to maintain the motor at such speed to keep the second synchro in step with the first, which is coupled to the friction wheel. In doing so, the servo motor had to make fifty revolutions to one of the synchros, in turn driving the tachometer at a rate within its range of usefulness. As persons familiar with this type of system will readily recognize, stability problems were enormous, resulting in its being discarded as a system for shop use.

The system recently developed and in process of being engineered into a shop version is shown in Figure 5. It consists basically of two precision, single turn, continuous rotation potentiometers coupled to a single shaft and to a friction drive wheel. In this system, with the speed of rotation constant, the potentiometer-capacitor-microammeter circuit on the left consists of a basic R-C rate generator. If speed is constant, current through the meter is constant. Components and voltages are balanced so that, in the situation shown, the current through the resistor R is equal to that in the microammeter. This is true at

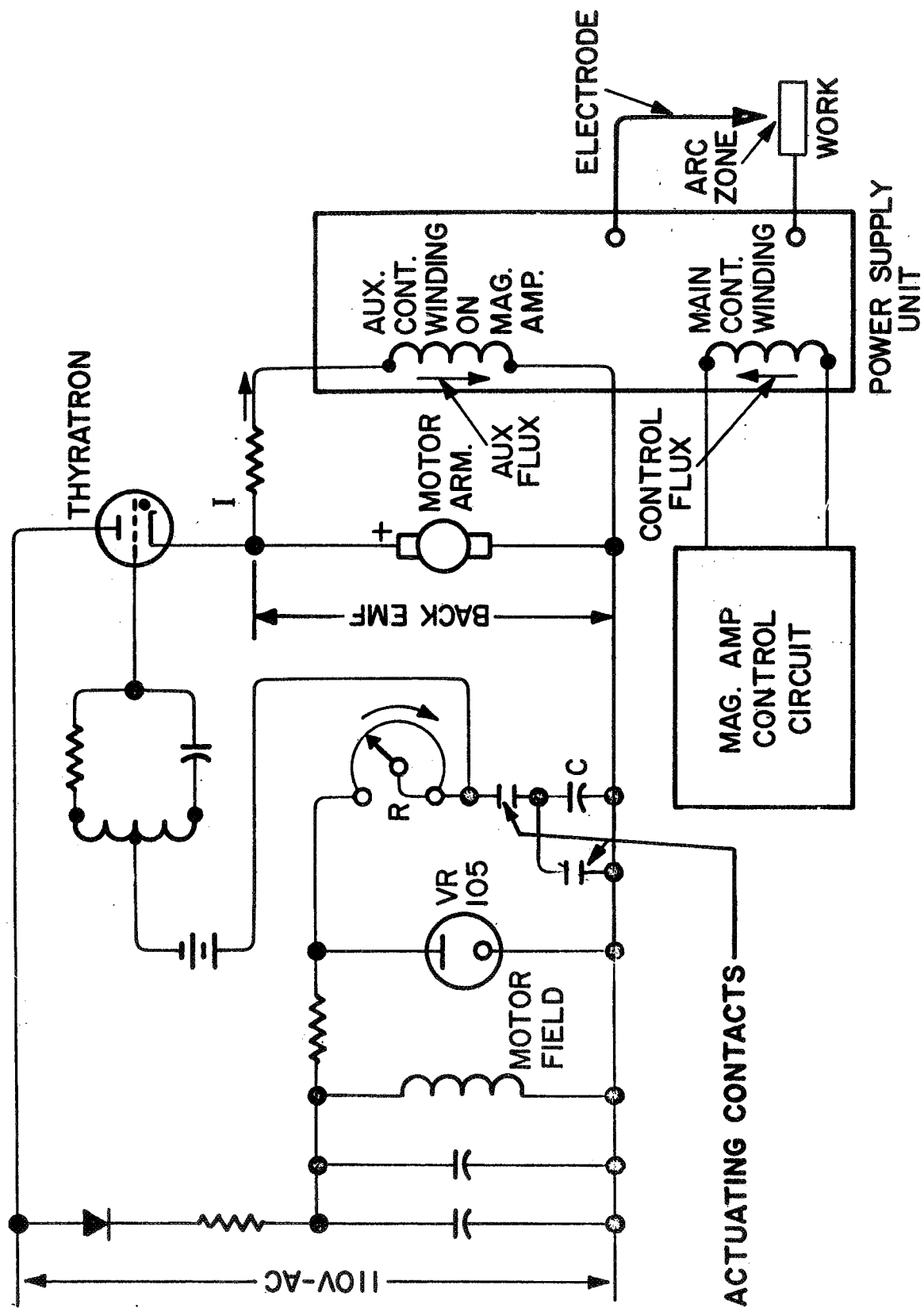


Figure 3. Elementary Diagram of a Taper Control

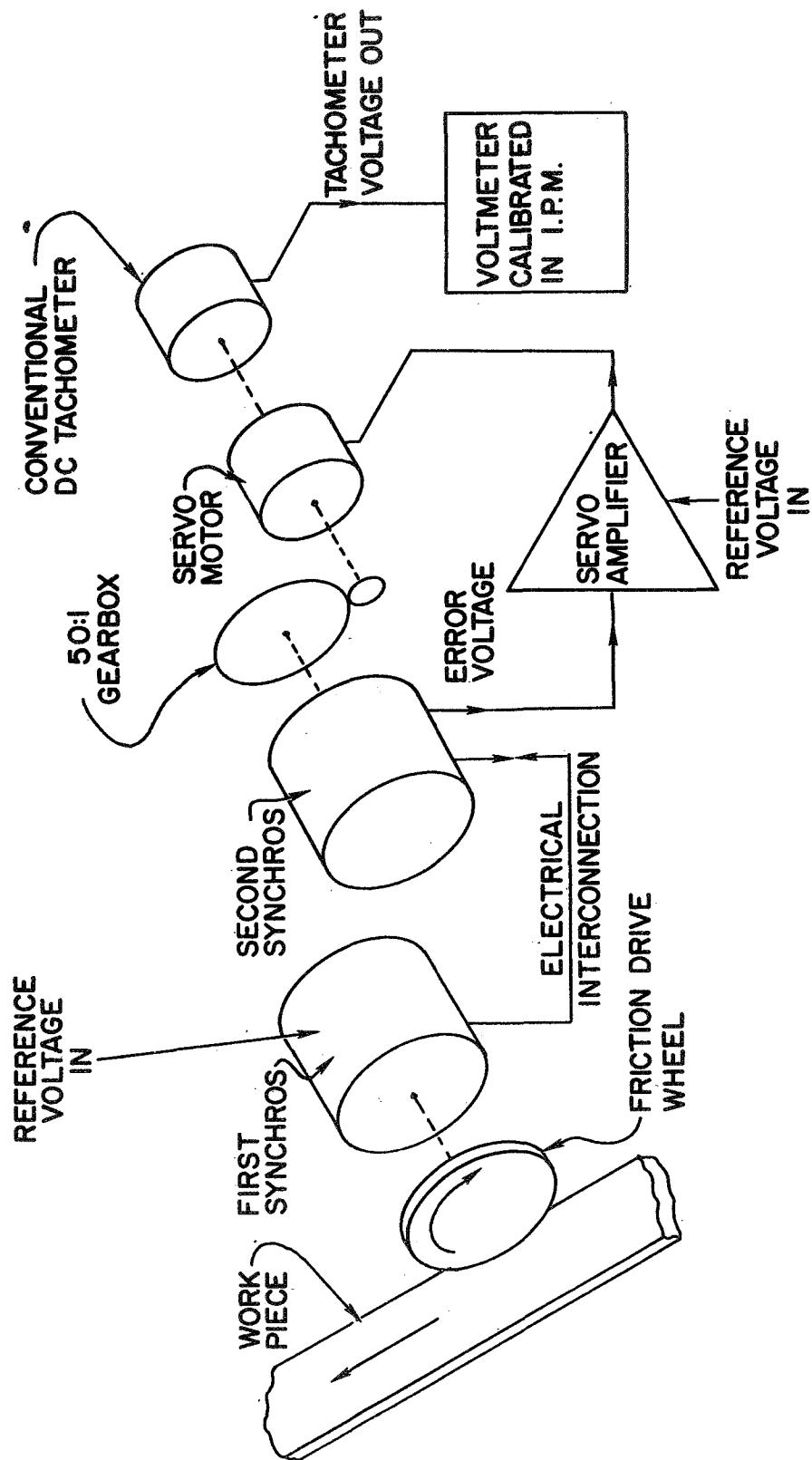


Figure 4. Block Diagram of a Low Speed Tach Using Synchros

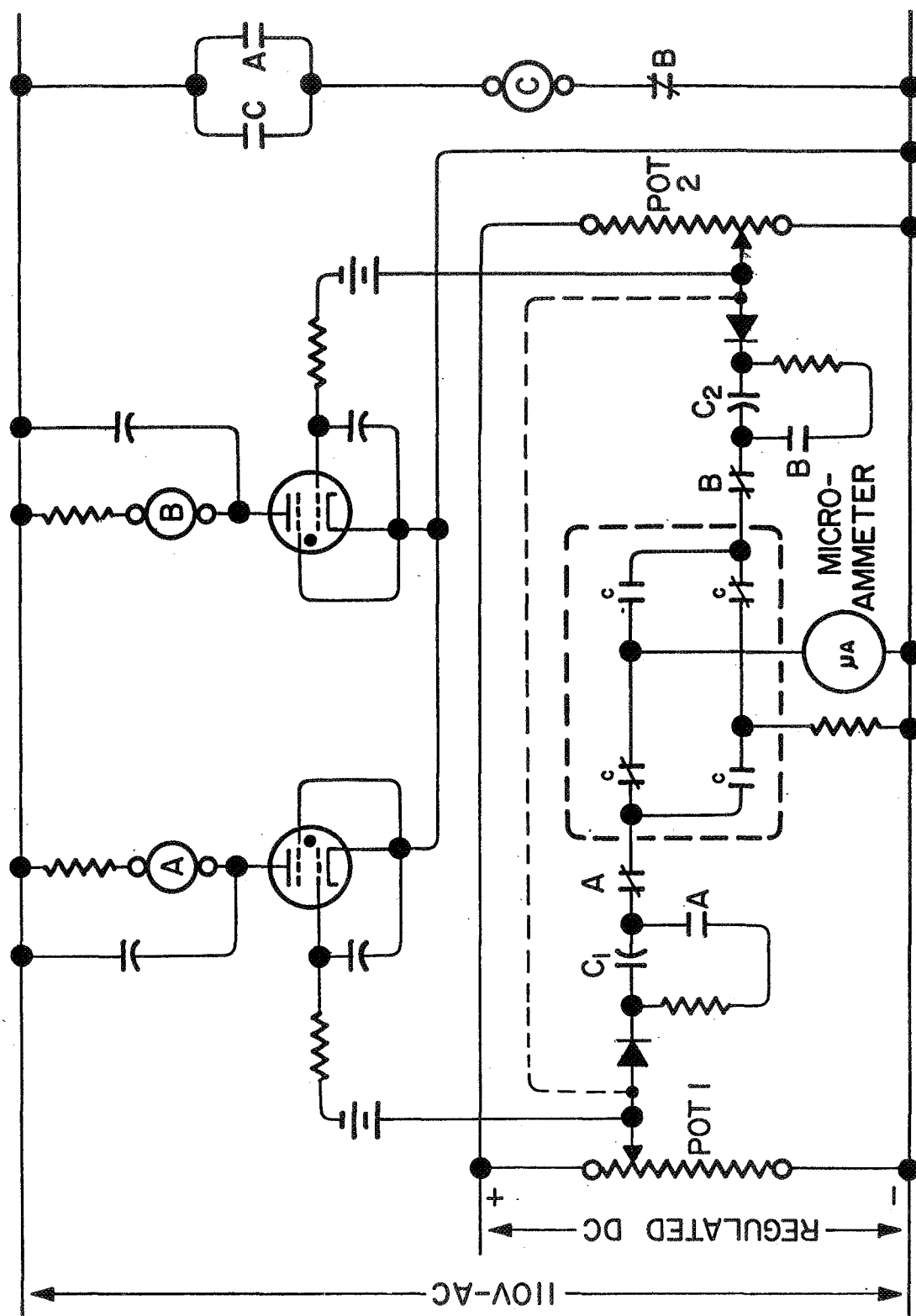


Figure 5. Elementary Diagram RC Rate Generator Tach System

any position of the potentiometers except near the ends and during the few degrees of discontinuity. Thus at the instant shown, the microammeter would read the same regardless of whether it was being fed by the R-C circuit to the left or the right. The thyatron-relay sequence is designed simply to transfer from one potentiometer to the other at the proper time to avoid end effects and discontinuity in its present form, the system is amazingly accurate, sensitive, and linear in the range of one-quarter to ten RPM. The basic ingredients are good quality capacitors, 0.5 percent precision potentiometers, and a quality regulated power supply, which in this case, is commercially available at about \$250 cost.

These cases are not presented as standards of excellence, but as illustrations of the use of simple measures to accomplish certain ends where previously more complicated methods had been tried.

In this discussion, I have tried to objectively evaluate some of the problems that have resulted from the rapid advances in welding technology, especially in the areas of controls and instrumentation. I have suggested certain partial solutions, not necessarily in the realm of the control engineer. But the point I wish to emphasize most is that the control engineer is, with the vast store of tools and technology at his disposal, in the best position to make significant improvements in the field of welding technology. The obvious way to accomplish this is to concentrate on the development of simpler, more reliable control schemes and apparatus. That this must be done is an obvious necessity.

## DISCUSSION

Mr. Kelker: Are there any questions that you people have that you would like to present to Bill? It was quite conclusive in itself. There is a question way in the back, Bob Hackman?

Mr. Hackman: It's not a question; I think it is just a complete endorsement to what Mr. McCampbell said this morning. I think this is good sound thinking, and it is certainly the only direction to go.

Mr. McCampbell: Thank you very much, Bob.

Mr. Gaw: I also agree that the thought was excellent. I would like to inquire in what areas you found redundancy played a part in reducing the reliability of welding machines and equipment?

Mr. McCampbell: Well, first, we sometimes build special purpose items or multipurpose items of control. We have a power supply, for instance, which has MIG and TIG capability. The MIG power supply essentially would be, say, a \$1,200 or a \$1,500 item if we went to a single purpose unit, and we would not have these other things in there to give us trouble. In a given weld for a given application, we may have equipment there that has up-slope functions and down-slope functions; and all the things that, to begin with, give the operator more buttons to push, and they give the trouble shooter more wires to look through when trouble does develop. If we are going to make a simple MIG weld where we don't have any need for certain of these functions of up-slope, down-slope, I believe that we should give the man in the shop absolutely no more than he needs to do the job. If he doesn't need up-slope and down-slope, then let's not give it to him, because it can cause trouble.

Mr. Gaw: With respect to the discussion that you just gave me, is this consistent with the economics of buying the minimum amount of equipment to do the maximum number of jobs?

Mr. McCampbell: I am not sure that I understand.

Mr. Gaw: Well, to restate the question, you described going about putting a welding shop together to do certain specific jobs with a piece of equipment to do a given job. Doesn't that run into nearly as much money or more than buying multi-purpose equipment?

Mr. McCampbell: In some cases, it would; but we have here two different situations. We have on the one hand, R&D personnel who must start with a piece of equipment that essentially can do most anything, because when the man starts, he may not have made up his mind whether the best way to go is MIG, TIG, or whatever. So he needs this special laboratory-type equipment. But when we get some equipment to go out into the shop area, it should be as simple as we can get it. I believe that this would be a more economical way to go than the way we have in some cases, where we actually bought the equipment with all the special features that R&D needed and then sent it to the shop.

Mr. Dwyer: I also would like to give you my congratulations for an excellent speech.

Mr. McCampbell: Thank you, sir.

Mr. Kelker: Gentlemen, on behalf of the three speakers, Mr. Taylor, Mr. Manary, and Mr. McCampbell, we want to thank you for a very gracious and attentive audience. And now I turn it back to Mr. Orr.

## PANEL DISCUSSION

Bob Hoppes will have a list of the attendees made up and mailed to you, so that each of you will get a list of those in attendance. I'd like to have Gordon Parks come up now if he will, please. Gordon is chief of our Welding Development Lab, Marshall Space Flight Center. He's going to take over now and describe a little bit to you about what our panel is going to do for us this morning.

Mr. Parks: It's most gratifying to have been a part of integrating such a collection of talent in the State of Alabama. My apologies to Mr. Wallace. Thought seed for this symposium began to germinate some time ago with the recognition of our inability to answer all the technical problems that were being generated with the welding of 2219 aluminum alloy; and, I might add, some of the other alloys. Consequently, we arrived at a plan to obtain a consensus of opinion from industry. In doing that, Mr. Hoppes, who has done a wonderful job of setting up this symposium, made a tour, along with Bob Baysinger of Kaiser, to feel out the problems of the aerospace fabricators. Strangely enough, we found that there were a lot of sympathies and much commiseration. Bringing back the story, and adding it up, we found that many people were searching for the same perfection that we were attempting to obtain here. Many of us were going down the same road and were duplicating each other's work. As a result, we summarized this, and I think that summary is available now as a handout, as an Internal Note, that might be interesting to some of you, or all of you. We finally collected the talent that is here; and then someone put my name on the program to summarize the papers that were presented to make a technical summary. To some of you who have received a copy of the papers that have been presented, I found it was extremely difficult. All these years I have become pretty adroit dodging such assignments, and yesterday evening I was successful in passing this one on to a very capable and diversified group, headed up by Hiram Brown, who will act as chairman. This group will attempt to draw out discussion and answers from the participants---I said precipitants yesterday---to come to a conclusion and perhaps an objective from this general symposium. With that, I would like to turn that responsibility over to Hiram Brown and the panel.

Chairman, Mr. Brown: You know, some years ago, I was making a talk to an Indianapolis chapter of Associated Society for Metals. I happened to be about the third speaker on the program, and each of us insisted on having our say, which became quite lengthy. About half-way through my talk, I saw three or four men coming down the aisle and I noticed they were carrying a coil of rope. So, I said to myself, "Of all the parties I'm going to attend, a lynch party isn't going to be one of them." So, I grabbed my notes and started for the exit. The program chairman said, "Sit tight, Hi. It's me they're after." The reason I tell you this story is that I'm sure that nobody here today will say that about Mr. Kuers, Mr. Wuenschel, Mr. Orr, Mr. Parks, Mr. Williams, Mr. Hoppes, and all those who made this thing possible. I'm sure that I speak for all of us when I say that we certainly appreciate the care, the detailed handling, and the courtesy that's been extended to us all during our stay here in Huntsville. Am I right, fellows? Now, you've all heard a great many ideas expressed during this symposium down here, both direct and devious, but at least prolific. And in trying to arrive at the summary that 'Gordy' wants, I feel a little bit like the fellow in New York City that walked up to the Irish cop and said, "Say, can you direct me to the Methodist Hospital?" And the



Irish cop said, "Sure, and I can be doing that." He says, "Cross the street---this is Fifth Avenue---turn to the right two blocks and there's Saint Partick's Cathedral." The guy said, "You didn't understand what I said; I want to go to the Methodist Hospital." "Wait till I tell you," he says. "You go to St. Partick's Cathedral, go up the stairs, and there's a big door there." The guy said, "I know, but I want to go to the Methodist Hospital." The guy said, "Just a minute, I'm telling you. You go down two blocks to Saint Patrick's Cathedral, go up those stairs, go in that big door, walk about 50 feet and yell 'To Hell with the Pope,' and before you know it, you're in the Methodist Hospital."

Now, I think that's about where we are in this program; I'm not quite sure. I have taken the liberty of just making a brief and I'm sure over-simplified summary of the things that have been discussed. I broke it into three general categories which you may or may not agree with, but these will pin-point it so that we can discuss it. I'd like to outline those for you, so that you can go to work on the panel. First, in the metallurgical area, we've heard considerable discussion on the causes of porosity. We've heard it ascribed to hydrogen, we've talked about water vapor, hydrocarbon, environmental effects; we've heard the vendors told that they couldn't supply good quality base metal, their filler metal was lousy, and that this affected weld porosity. We've had suggestions from the supplier on how to check weld wire, what happened with the carry-over of gas from the bad wire into the weld. We've heard the theory of how porosity is formed, and nucleation and growth phenomena versus the solidification rate. We've heard porosity related to the time and temperature effects where we went through low speed and low porosity; medium speed with high porosity; and high speed with low porosity again. We've heard about mismatch and porosity not being additive.

Second, we have covered a statistical area: The Welding Parameters on Electron Beam Welds and Statistical Approach of Design, Control, and Evaluation of Test Welding, in which we were told how to work on this cube and find all the corners of the cube by statistical methods rather than trying to do it in the simple hand way. We've heard an analysis of quality problems in which we were told the astonishing news that 85 percent of the problems were found in this investigation to be of a human nature, 12 percent tooling and equipment, and 3 percent others, including material. We've heard about the strain distribution across aluminum weldments.

We also had a third area of equipment and operation. We've heard discussed heat transfer, slow travel rate and fast travel rate, and the implied suggestion that if you're going to use a slow travel rate, use copper backup to take away the heat more rapidly; if you're going to use a fast travel rate, use stainless steel to slow down the heat dissipation. We heard a Spectrographic Monitoring of Gas Shields for Atmospheric Contamination. We heard of the efforts to achieve Self-Compensating Gas Tungsten-Arc Welding; Torch Guidance Using Closed Circuit TV; and Equipment Precautions for High Quality Welds in Thick Aluminum, including how to clean the wire just before it went into the welding operation. And, we've had a look this morning at some Dependable Weld Control Systems. This is a pretty wide area, and there have been many things said. The thing that the panel has to do, in order to summarize this for you before we get through, is to find out how much has been fact and how much has been fiction, and your answers and questions are going to point this out. I'd like to introduce the panel to you, if they will stand up so they can see who they are going to insult this morning;

Mr. Hawkins, Mr. Lenamond, Mr. Bandelin, Mr. Rish, Mr. Schwartzbart, Mr. Dyer Mr. Waite, Mr. Rieppel. Mr. Hackman, Mr. Davis, and Mr. Vilkas 'These are your gentlemen. You can fire when ready, present anything that you do not agree with, or that you wish to agree with. Fire away!'

Mr. Chyle: On this matter of porosity in aluminum welds, we heard yesterday a number of papers all in the same way, indicating that porosity is almost unavoidable, and yet, we had a few speakers that said, "Well, if you can control these things, you'll have a weld that is free from porosity and that is controllable." I'd like to know from the panel whether someone can say that they do have control of porosity, that if you take care of some of the variables, like the wire and a few other things, that you can say, "Yes, we can guarantee a weld that'll be, say, NASA's spec on radiography."

Chariman, Mr. Brown: Who would like to try this one for size?

Panel, Mr. Baysinger: Concerning the porosity, I think that the basic problem is that it is uncontrollable, because I've looked at many, many feet of X-ray film, 100-foot long welds, and this is the frustrating thing. Portions of this weld will be perfect, this is true, but then, all of a sudden, something changes and you get a portion of the weld that is not good. Then, it will clear up, and it will go on, weld merrily for 50 feet, and everything is fine. There are other things that are even more frustrating in working with pressure vessel people who have X-ray requirements on their 100 percent X-ray, field-erected, very large aluminum spheres. We find that the welding wire equipment is back in the ice ages compared to what the space industry is using. They take wires right off the shelf with no control, no specification, no check on the gas, no check on the equipment. Yet, much of that footage is good. Then all of a sudden you'll hit bad seams, and when that happens, the whole seam will be bad. This is basically the problem: It is uncontrolled. You don't know what is causing the difference between the good and the bad. The summary of papers here was intended to present ideas on what the causes might be so that the welding engineer could take a look at the various possible causes in the hopes of correcting these, that he could consistently get good welds. My opinion is that if with a million dollars worth of equipment, very extensive quality control, checking, draw filing, and everything, you still can't make a good weld, there is still some factor operating that is out of control. So, I think that your analysis that it is not controlled is quite correct.

Panel, Mr. Vilkas: I believe that some of the answers can be found in studying the arc physics. For example, most people know that the deep penetrating welds are made with very, very low voltages. What is the relationship between the physical arc length, or in this case, for example, voltage, and the porosity level? You have perhaps tried yourself and know that with the MIG welding there is a certain optimum arc length which produces the least possible amount of porosity in the weld. The changes in these parameters, like arc length, should be recorded, and correlated with the porosity level. This we have tried, and I believe we will publish soon the simple methods of correlating these factors. There are other things: for example, the shape of the arc. What is the relationship between the shape of the arc and porosity?

Some of the studies already made by Douglas indicated that ripple has something to do with these phenomena; so does the penetration. So, there are physics involved which should be studied and compared under production conditions. Let's use production conditions which are known. Let's use the joint designs and the thicknesses which are known and evaluate porosity with respect to these parameters which are shortly described as arc physics.

Chairman, Mr. Brown: Does this answer your question or do you want to go some more?

Mr. Chyle: Yes, but I have a second part to that. Now, if the consensus of opinion is that there is still an uncontrollable factor in regard to porosity, would you say that if we observe all the scientific principles, we have hope that we can in the near future, by scientific control, eliminate porosity?

Chairman, Mr. Brown: Perry, would you like to comment? Mr. Rieppel?

Panel, Mr. Rieppel: I think we can start at this fairly simply. We won't have porosity unless we have gas, and that gas is hydrogen. Now if you don't get it in the weld, you won't have porosity. There are several things, many things, you can do to keep it out, but you'll probably never reach the point where you'll keep it all out, consistently, all the time. You are trying for perfection which you'll probably never reach. But, if we observe the things that we know, in terms of keeping it out, we could go a long way in this manner. Now, the other things that we do, in terms of controlling speed and all this sort of thing, just simply control whether it comes out or whether it stays in. I don't think we ever will get to this point of perfection. If we had no gas that could get into the molten metal, in the weld, we would not have any porosity. We can keep most of this out, most of the time, but there are inconsistencies that come along. We will probably never reach this point of perfection, and there is no use trying. But, we can keep it down to a low level, and probably by learning more than we know now, we can maybe squeeze that down a little further and consistently. But, I don't think that we will ever get rid of it completely. It's not even worth trying to do. I don't know if this answers it or not.

Chairman, Mr. Brown: Does this answer it?

Mr. Chyle: Yes.

Panel, Mr. Davis: I think that we, as welding engineers, try to control our welding processes and all variables so that we obtain clear welds within some statistical probability. We realize that we have some cleanliness control. We can't control it 100 percent, neither can we control the equipment 100 percent nor the manual operations that go into the joint before it reaches welding. So, therefore, we put some statistical limit in it ourselves, knowing very good and well that we're going to have some porosity. But, now there's another statistical variable that comes in here, that multiplies into this, and this is the manufacturing of the base metal. The people who are manufacturing this metal have some probability

that their material is going to have a minimum amount of hydrogen, some 99 percent probability, based on a 95 percent confidence. This means that in 99 batches, or if you run 100 such batches, 95 of these batches will fall within this 95 percent probability, and the other would fall in this 5 percent outside. So, therefore, we have a statistical probability of introducing porosity, not from just the welding operation, but from the base metal, and even though we establish ours on some confidence level in the welding field, we have to add to this the probability of the manufacture of the base metal.

Panel, Mr. Hackman: I'd like to make several suggestions which aren't perhaps revolutionary but a little different than what we have heard so far. First, of all, I think that if you look at all the different welds being made on the Saturn V Vehicle today, you'll find that the vast majority---and I think I'm correct, maybe someone will jump up and tell me on this---are not giving any real problem as far as porosity. The problem lies in the 3 o'clock welds, not in the other welds. So, it's a case of positioning. The metal hasn't changed, the process hasn't changed, the control hasn't changed, nothing has changed. Only one thing has changed: position. So, we get an uncontrolled situation on our 3 o'clock welds. Now, the decision was made a long time ago that the large vehicles would be made with soft tooling, and certainly it's not for me to question this decision. However, when we went to soft tooling, this meant that we were stuck with the 3 o'clock welds. Now, if it's really important, vitally important, that the quality of these welds be improved or the program isn't going to go anywhere, there's an obvious answer, and it doesn't require any R & D study at all. It's a simple case of rolling these welds over. And, while this may seem like a rather funny thing to suggest, to take a vehicle so large and roll it, or even cock it over partially, I can tell you that I think it's completely practical because the U.S. Navy has built an atomic submarine out of two inch plate which is 100 percent roll-welded. They roll-welded a complete submarine. So, I throw this out for a thought, that this is one area that has not been---I shouldn't say this, it certainly has been considered---but I haven't heard it brought up during the last three days.

Floor, Question: This is going to change the subject a little bit. If the panel is finished with getting rid of porosity, this has to do with the location of random porosity within the weld. One of the speakers yesterday alluded to the fact, and it was on the 3 o'clock weld, that porosity at the interface between the fusion line and perhaps the heat affected zone was a little more undesirable than porosity randomly spaced throughout the center of the weld. I wondered if I had heard correctly, and if this is the case, if there was an explanation for it?

Panel, Mr. Bandelin: The gentleman that gave that particular paper isn't on the panel today, but I think that I can slightly elaborate on it. In the many tests that have been performed, by many companies, this condition on the 3 o'clock welding, where we find the porosity at the fusion zone of the base metal in a more linear condition, has proven many, many times to be a failure condition much lower than the porosity that has appeared in the center or in a scattered condition. If you recall, yesterday I mentioned that my particular paper was not referring to linear porosity; I was referring to scattered porosity. We have found that this condition of a regular shaped porosity and globular shaped porosity in a linear condition, which appears

adjacent to the fusion zone directly against the base metal more or less, has considerably lowered the values. There has been propagation of cracking when loaded between the porosity conditions, and I would say, by far has lowered the property values many, many percent, below that of taking the same type of porosity and scattering it throughout the mass. It's not a factor of cross sectional area of reduction by porosity, but the actual location of porosity in relationship to the loads that are applied. Does that help you any?

Floor, Question: I gather that I was right and that there is concern about porosity in this area.

Panel, Mr. Bandelin: Absolutely.

Chairman, Mr. Brown: Mr. Schwartzbart, did you want to comment?

Panel, Mr. Schwartzbart: I think an additional thing that was brought out yesterday was that all the speakers who talked about failure zones, fractured specimens of any sort, remarked that failure occurred in fusion zone or near it; which would mean that the porosity in that region, just by reduction of cross-sectional thickness would be more deleterious than porosity, let's say, scattered throughout the region of the weld where there's additional metal.

Floor, Question: I want to address this to Mr. Rieppel in particular. Almost all the slides and pictures we've seen on porosity have shown a nice circular appearance on the X-ray film, and yet, here at Marshall, almost all the rejectable porosity we, in Quality, find are the so-called porosity with tails or sharp termination points. We see many instances of a long stringer-type appearance in the weld rather than a nice, spherical, round gas bubble. I'd like to know if, in your opinion, these hydrogen gas bubbles are in the weld, or is there some other explanation for them?

Panel, Mr. Rieppel: Well, to begin with, I think we can say that they are hydrogen. We don't know of anything else that produces porosity in aluminum. The reason that you have the trailed out shapes that you're talking about is that you start a bubble, and maybe three quarters of the perimeter of that bubble freezes which leaves a little piece of the surface of that bubble exposed to liquid metal. This will expand and will keep on coming out and growing larger until it finally freezes in for some reason. We see this in steel also, when you have porosity that starts and grows along as the solidification continues. One part of that bubble had liquid metal on it. It grows larger and squeezes out a little further and just keeps on going until it either freezes in or there's no more source of hydrogen for it.

Chairman, Mr. Brown: Which is the last to form, Perry, the tail or the round part?

Panel, Mr. Rieppel: Well, the last part to freeze will be the largest part of it usually because this type of thing as it grows, starts small and keeps getting larger. It will not be round. Both ends will probably be round, but the largest end is the one that freezes last, as a rule. The other end may or may not be, but probably will be round. It might have started

forming on some type of inclusion, and if you searched the very beginning, you might find a rough surface of some kind there, but chances are, it'll be nearly round from the beginning, except for one small part of it.

Chairman, Mr. Brown: Mr Schwartzbart, you want to comment on it?

Panel, Mr. Schwartzbart: I offer an alternate explanation, which we think is the case. From metallographic work we've done on porosity where we see round pores with tails, in which case the tails have sharp ends, we think the porosity is caused by gas coming out and nucleated at sites of micro cracks. You have a micro crack first which nucleates the generation of the micro pore, and we think this is the explanation of the type of defect that you are talking about. It seems to me that the other type of mechanism might be more apt to give you a tear shape or round end of the tail, which we haven't seen in our metallographic work.

Panel, Mr. Rieppel: I think this would be quite easy to check because, if there was a crack, this crack had to be in solid metal or in nearly solid metal. Again, if you get a bubble at the end of that, there must be a liquid face for it to form in. So, you might start with what was a crack, which extends to a freezing face, and there accumulates a bubble on the end of it. But, I think that you see this long trailed-out type of porosity particularly in steel---we used to call them worm holes---and they follow the pattern of the freezing of the bead. They start to nucleate one way or the other but there is a liquid face on one part of this where it keeps growing, and if you look at the sides of it, you'll have a bunch of little scallops on it as it progressively grows along. I don't say that Harry's analysis is wrong, but I think if you had a crack, you're close to solidous, and one end of that crack then must have been at the liquid phase or very near it.

Panel, Mr. Schwartzbart: I think that the crux of the matter is whether a micro crack can nucleate a pore. We think it can, and we think this is the explanation. Probably the truth lies somewhere between the two.

Mr. Saperstein: I have a comment pertaining to the discussions that have already been made, if I may make it. In addition to the possibilities that have already been offered, the British many years ago discussed another form of porosity, which I think we're all aware of, tunneling type of porosity, which has nothing to do with hydrogen; which is due in fact to very high current densities, and high gas flow rates, and is a mechanical effect more than anything else, with attendant high solidification rates. This sometimes can have the appearance, in fact always has the appearance, of a long pore that parallels the longitudinal axis of the weld. It has been established that such a defect is caused by the entrapment of the inert gas.

Panel, Mr. Rieppel: May I comment on that? When it happens, it gets the so-called puckering.

Mr. Saperstein: Not always.

Panel, Mr. Rieppel: Well, it gets very close to it. Your welding process is out of control or you won't get it.

Mr. Saperstein: That's right.

Panel, Mr. Rieppel: Completely out of control.

Mr. Saperstein: No.

Panel, Mr. Rieppel: Well, for all practical purposes.

Mr. Saperstein: That is, if you find after the fact that it's out of control, and you see such a defect, I will agree with you. It's not always obvious that it's out of control when the defect happens.

Panel, Mr. Hackman: Following up on that, just one more comment. We made excellent tunneling which is just, I agree with you, trapped inert gas. Where we did not have a puckered surface, the outward surface was excellent. This occurs under three considerations, or four perhaps: (1) very high current, (2) very high gas flow, (3) relatively thick plate, and (4) generally on alloys having a narrow freeze range such as 1100 or 3003. And particularly, you'll walk right into trouble if you attempt to do this with straight Argon. Quite often the substitution of the Helium rich mixture, and perhaps if you have a choice of filler wire, getting a filler wire with a wider freeze range will overcome this. We have produced this, a lot of it unfortunately, through using Argon and working on these particular alloys that do have this narrow freeze range.

Mr. Cline: I note, with respect to porosity and defects in general, that we have seen a number of slides and examples of black dots, before our eyes. In addition to seeing these black dots and referring to them in various forms of terminology, on a properly prepared specimen there should also be some other things that you would be able to see. It causes some concern from a metallographic standpoint when you only see these black dots, and you don't see some of the other things that you know are there and should be there. I think that in the evaluation of porosity or defects, or internal inclusions, that this is oftentimes a good measure of whether we're having proper preparation or not. Do we actually see some of the things that we know should be there. In some of the presentations of cross sections, looking at defects, it was not apparent from the slides or the photomicrographs themselves that we were seeing some of the things we should see there.

Chairman, Mr. Brown: What kinds of things did you have in mind?

Mr. Cline: Specifically, in one of the papers this morning, looking at the cross sections of wire, there's no apparent metallurgical structure, yet in the as-polished condition, some should be apparent.

Chairman, Mr. Brown: Is it the fact that the detail is not brought out in the transmission of your picture sometimes?

Panel, Mr. Schwartzbart: Would you expect to see it in the unetched condition? What would you expect to see unetched in addition to the pores?

Mr. Cline: I think there are many constituents that should appear unetched. We should see some of the insoluble constituents that are there, and in the case of the aluminum-copper alloys, we should see the copper phase.

Chairman, Mr. Brown: Isn't there a good chance that the detail may be lost in reproducing these? Sometimes when you etch, you're etching to bring out a particular thing, and you've not etching for the whole thing. You must etch differently for each one. I think this leads to it sometimes, doesn't it?

Chairman, Mr. Brown: These are unetched? Well, that's even harder to bring out the detail, I think.

Mr. Cline: It was a general note that I think this should be taken into consideration when we're looking at defects because in the polishing of metallographic specimens in aluminum, sometimes you're going to see some artifacts that could be construed as defects or porosity, and they aren't. One measure of this is, can you see some of the things that should be there?

Chairman, Mr. Brown: On the microscope, you're not talking about the X-ray pictures we saw?

Mr. Cline: On the microscope only.

Chairman, Mr. Brown: Mr. Hawkins, do you want to comment on that?

Panel, Mr. Hawkins: Well, I think that understanding the principal used, in the cleaning at GDA---I'm sure this is the paper he's referring to---you actually get a surface condition which looks like a weld that has been made because you have actually drawn an arc, and without etching it, it is not going to show up nor is it going to be obvious blown up 200 times, because I have seen some samples that they have done where they have etched them, and you can see all these items. Now the original slides did show this. But I think that in the paper, transmitting it through taking the photographs, a lot of it was lost. But you could see weld ripple; in other words, you could see displacement of some surface metal to some degree in the original slides.

Mr. Wuenschel: Having a panel with a large number of outstanding experts in the field, I wanted to take this opportunity to find out something. If we talk about welding, we have there a beautiful means to come up with a one-piece structure. Welding enables you to take the parts and to make them one piece. Now, it has some disadvantages. There is something like a weld efficiency, so you have to give a little bit in local weld land and this is just a weight penalty. And if you have such an inherent occurrence, like porosity, it more or less belongs to the total story of weld efficiency. That means you can't get it all filled up; there are little voids. You can overcome it by just making your weld land a little bit thicker, which means lowering your requirement, and it will be a little bit more of a weight penalty to get a one-piece structure. But, there is something else, and I think that wasn't mentioned at all here. You have another inherent disadvantage in welding something together; you have shrinkage and warpage, and this is what, desirably in many cases, rules out welding. I think, from the point of porosity and weld efficiency, that if you would perfect TIG or MIG, or what have you, and get rid of the porosity, and if you would do something to the alloy to avoid any degradation by heat affected zone, like in alpha titanium or so, you would get 100 percent weld efficiency. Then you would have everything. But I think a welding process should be considered with respect to minimum shrinkage to make that weld



universally available so that we could do more things like looking into the tank of a big vehicle. You have to have stiffeners to avoid buckling, and right now we mill it out of a two-and-a-quarter-inch plate. If you look toward the larger vehicle, you would like to have a high stiffener, 4 or 6 inches, and you would just have to have the stuff to mill it out of full plate. If you want to joint that, and even if you had a welding process which was perfect or that would efficiently weld, and the weld land wouldn't play a major role weight-wise, the prohibitive factor would be the tremendous influence of shrinkage. The big parts would have to be reshaped after welding, and suddenly that whole approach doesn't seem too attractive. So I want to find out here from the panel which welding process, not only considering highest weld efficiency, or, let's say the most fool-proof operation, will provide the least disturbance with respect to shrinkage. Which welding processes are the attractive ones to be looked into. This is obviously something we have to do in the future and also to support in the future, whether it is needed right now or not.

Chairman, Mr. Brown: Mr. Lenamond, would you care to comment on that?

Panel, Mr. Lenamond: This may be, as you say, a little bit in the future, but in thinking of the porosity, I mean the shrinkage and the stresses that are set up here in building or fabricating these vessels, one means that we have looked at and are doing some preliminary work in is that of 'cold welding.' Now, a lot of people have looked at this for a long time from different aspects. NASA is looking at it in many instances from the standpoint of preventing things such as galling, and are taking great means to prevent this. But, I just wonder, are we really looking at it hard enough and long enough from the standpoint of actually making this thing work? One means that would work is getting two surfaces flat on the atomic scale, because, in effect, you have two factors here--a flat surface and a clean surface. Admittedly, you're going to have this thing of absorbed gases to contend with, but I do think that we should give this a great deal of thought.

Panel, Mr. Waite: I believe that in the choice of a process we also have to take into consideration the procedures that are necessary to use that process properly, including preparation. I feel that the process which is applicable to vertical welds is not necessarily applicable to the horizontal welds. I also feel that a great deal of the problem can be eliminated by edge preparation; probably soft tooling prevents an optimum edge preparation. We have heard a lot about porosity as a result of gaseous parent metal on occasion. This can be almost completely eliminated by the use of proper edge preparation, so that we fuse not a large cross-sectional area of a tight square butt joint, but rather fuse merely a shallow surface on a properly prepared edge. This would eliminate, I believe, a great deal of porosity, without any change in the gaseous content of the parent metal. Then, also, if we have the edge preparation to accommodate our process properly, we can, with a given energy level, travel at a higher rate of speed through the addition of a greater amount of filler wire. We still have the filler wire problem to contend with but that is a single problem and not a multiple problem of base metal, improper joint contours, and filler wire, as well as equipment. I think that we must look at the choice of process with all these other things in view. In other words, if a square-butt joint is not suitable in the horizontal position for one process, then we must find another process or another joint type that will be suitable to give us an optimum result in that welding position.

Panel, Mr. Dwyer: Well, the question's a very difficult one to answer. I agree with Mr. Waite that for a given job, I would assume that among the number of welding engineers I could get fifty arguments about which would be the best way to go for a particular job on a particular type of metal, and I would guess that in many cases, five or six of us would all be right, if five or six of us were talking about different things. I do know that the welding industry will, in the not too distant future, (and I think that we're compounding the problem now,) have more processes available to you than what you have now. Some of these are going to be fast-moving with intense heat for a small area that may get you out of some of the problems that you have mentioned. But, on the other hand, frequently you people in aerospace are very much like the guy that just gets the shower adjusted when someone flushes the toilet. You come along with new materials, with new requirements, and we have to go back into the lab and take a second look at a different process to come up with an answer to the problem that you're giving us. And really, in my own estimation, there just isn't a cut-and-dried answer or process for a given problem.

Panel, Mr. Schwartzbart: Well, I'm not sure it's necessary; however, I consider that a very direct and precise question has been made, and it has a very direct and precise answer. Distortion is simply a function of the amount of energy, the amount of BTU's required per an inch of weld. Anything you heat inland from the surface you're trying to join is wasted. Welding engineers give a lot of thought to how to get the narrowest heat-affected zone, the narrowest heat to make a given distance of welds with the least amount of energy. Some processes have been specifically named. There is no one process to do all the joints, and the practical considerations vary from joint to joint and structure to structure. Certainly, electron beam, we know from experience, is one of the most attractive from the point of view of these distortions.

Chairman, Mr. Brown: Mr. Wuenscher, I think that you're in a position like the farmer who one time put a question to a very elegant speaker. He asked him if he knew something, or if he thought he knew something, and he said, "I don't think, I know." And the farmer said, "I don't think I know either."

Mr. Wuenscher: Normally, if you look back in history at the different developments, you reach a point where you have many approaches in the mill at the same time, and when everything matures, finally you end up with just one solution and nobody else thinks about the other solutions any more. Now, in your opinion, is there one out-standing welding process, or maybe a couple of them, which might win the race? I mean, if you look at electron beam, you have the trouble with the vacuum chamber. If you tried to get that beam out into normal inert gas environment, there are other problems. Then, there is, for instance, another type of joining: defusion bonding—that seems to be a beauty-or explosion welding. Now there might be a lot of deformation, but from our point of view, whenever you look toward the large vehicle application, you might need a hundred tons of cerocast to embed the parts which you want to explosively weld together. This is very heavy tooling, and after the operation you have to melt the tool away. Out of the available processes, high frequency joining is very attractive, but it has mechanical requirements. Obviously, the TIG and the

MIG seem to stay with us. Which other processes seem, in the near future, to be the next valid competitors?

Chairman, Mr. Brown: We could spend all morning on this with the panel, so I'm going to allow Mr. Hawkins the chance to suggest this panacea to you.

Panel, Mr. Hawkins: I think the most promising thing that I have witnessed in the past year traveling about the country and having the opportunity to have used this thing myself, is a combination between the TIG process and plasma, which will be a constrictive arc between two torches. This is the nearest thing I've seen to electron beam out of the chamber with the electron beam characteristics in welding. Here, you're going at high voltage, at very high frequency, at very low current, and you can travel through terrific thicknesses along these lines. I think that this is probably the most promising thing I've seen. It's a combination of TIG and plasma.

Chairman, Mr. Brown: Mr. Rish, we haven't had any questions for you, today. What would you like somebody to ask you a question about?

Panel, Mr. Rish: I was asked to sit here in the event that there were some questions in regard to recording. I'm with Honeywell, and had a little experience down here in using recorders on some of the processes.

Chairman, Mr. Brown: Does this include instrumentation?

Panel, Mr. Rish: Yes, to a limited extent.

Chairman, Mr. Brown: Does anyone have an instrumentation question? We've discussed this today. Does anyone have a question that he would like to address to Mr. Rish? I don't want him to feel neglected up here.

Panel, Mr. Vilkas: I wonder how many parameters, for instance in TIG welding, up to now are instrumented?

Panel, Mr. Rish: My experience has been limited to MSFC down here, and as we stand right now, we have only been recording voltage and current. There is a plan to record wire feed rate and the machine travel, as Bill McCampbell talked about. We have discussed recording gas flow but have not done anything along those lines.

Chairman, Mr. Brown: Does that answer your question? Another question down here. Yes.

Mr. Cline: We have an instrumentation program in work. We are recording the arc voltage, the welding amperage and the travel speed with a Wayne George digi-tack pickup and differential amplifiers. The wire feed rate is by the same system. There is an additional hookin where we know if the amperage change is because the operator changed it or because the machine changed. The same holds for the wire feed rate and the travel speed. We have an eddy current instrument coil mounted on the wire feed system so that we can correlate any defect with the chart readout. This is again a development of technique in the development program where we are at least trying to pin down this many items and relate them back to the weld.

Mr. Schwinghamer: I hate to beat this thing to death on porosity, but it is a golden opportunity when you get this many experts together under one roof. I could make 180 telephone calls and get answers, but this would be quicker. What I really want to find out is this---I would like to address the panel and also, if I can't get a rise up there, somebody in the audience. Have you ever welded at the 3 o'clock position, gotten porosity, but proved to yourself, individually, beyond a shadow of a doubt, that you did really have adequate gas coverage; you knew it did not aspirate air, you looked at it with either Schlieren or otherwise, and you were positive you did have gas coverage, but you got significant amounts of porosity? If somebody can tell me that happened, that's going to change my whole philosophy of life.

Panel, Mr. Hawkins: At one facility of which I am not at liberty to divulge the name, they have run welds in a chamber, where they purged it down and back filled many times, and found consistently that they can get porosity at the 3 o'clock and can't get it even at the overhead position. Consequently, they themselves determined and made this a published fact, that in the 3 o'clock position, they were getting entrapment. So, they think that in the box they at least had adequate coverage.

Mr. Schwinghamer: They attribute this to the entrapment of the shielding gas, you mean?

Panel, Mr. Hawkins: That is right. It did not have a chance to bubble out; they even shook it at a high speed rate of vibration in order to try to aspirate this gas and get it out. They had more success with this particular feature than any other. But, how are you going to shake that big beast you have out there?

Mr. Schwinghamer: On launch, but then it's a little late.

Panel Mr. Schwartzbard: I went to clarify one point that came up now. He said entrapment of the shielding gas or hydrogen?

Mr. Schwinghamer: It was shielding gas? Supposedly?

Panel, Mr. Hawkins: Yes, it was the hydrogen that came from the carrier of Helium gas.

Chairman, Mr. Brown: It was in the inert atmosphere, right?

Panel, Mr. Hawkins: Right.

Panel, Mr. Waite: In this respect, manipulation, slight oscillation of the torch, has been used to great advantage in eliminating porosity and discontinuities with both TIG and MIG processes. This oscillation is not a sidewise oscillation, but an oscillation in the direction of the joint itself. This tends to move the fluid part of the puddle around a little bit more, and the agitation is necessary in getting the gas out of entrapment, which is probably due to the general viscosity of the puddle. Another method of stirring and eliminating the gas, that can be used to quite good advantage, is with an arc that is not entirely quiet, that is, a certain amount of arc disturbance also causes a stirring. We don't want the disturbance to be so great

that it results in spatter, but some arc disturbance does have a beneficial effect in stirring the puddle.

Panel, Mr. Vilkas: I believe that the efficiency of shielding can be observed as well as calculated. For example, some journals have been published about the jet action in the arc. It's not too difficult to calculate and find that the speed of the arc plasma can reach a level of approximately three times the speed of sound, at the settings you're using here. Now, if you calculate the amount of gas jetted through this arc, and then the gas available plus the fact that this gas is expanding, you will have a kind of formula that will indicate to you what kind of shielding efficiency you have.

Mr. McArthur: I am from Olin, and I have listened with great interest these past three days to this porosity discussion. I agree with both Perry, and to a lesser degree, with Bob, that we're always going to be faced with some of this, and it's probably not necessary to get rid of it all. However, I've also heard many mentions of the variables that contribute to porosity. I wonder if anyone on the panel has hung some numbers on the significant variables; in other words, just what are the significant factors in porosity, what percentage can we apply to the filler, to the base plate, to the shielding gas, to the arc lengths, etc? Because until we start to do this, there's not much use of working on a 2 percent significance when there's probably a 15 to 20 percent variable sitting up in front of us. I wonder if anyone on the panel would like to comment on this?

Panel, Mr. Waite: I would merely want to say this, that the importance of the variables, in my opinion, is entirely different for the MIG and the TIG process.

Panel, Mr. Bandelin: I'm the factious one of this panel. I know that they challenge me that way. I've heard much about porosity and I talked a little bit about porosity myself yesterday. I think that everyone overlooks the easy way to be confronted with a large problem. We've all heard many, many people say that we get porosity, we get it from many sources, and when you question what percentage did we get from this, and what percentage did we get from that, and what percentage did we get from the other, they vary with whatever the conditions are. But, I must repeat two things that should be brought to your mind and everyone's mind. We know we are getting porosity and we know we are getting many other defects, but let's stick to porosity a moment. I think that not enough effort has been put into what effect these different conditions of porosity will have on our end product. Not only from the standpoint of what we as individuals see on the radiograph, but do we train out radiographic personnel properly to interpret what they are seeing? You could have incipient melting in the aluminum itself that could change a density factor in your X-ray. There are many things that could change your X-ray results so that you're seeing this porosity. I'm, not referring to porosity strictly on the surface now; I'm referring mainly to porosity that's subsurface. I think that your problem is more than which particular percentage comes from the wire or from the plate material, or the source, or the tubing that carries the gas, or what ever it is. We should concentrate our efforts more on the effect of this porosity. And we can't see it all. Some of the micro porosity we never see. A very good case of a more serious condition would be in heavy plate. You may have incomplete penetration in the center where your plates are so close together that it is physically impossible to see this by any radio-

graphic means. We should consider concentrating more efforts on what are the real effects of the types of porosity we have and the other conditions that prevail. I'm not getting away from trying to get it better; we are all trying to do that, but we have this condition today.

Panel, Mr. Rieppel: I believe the question was--he'd like to have some opinion of which one of the basic sources of porosity may be the most important, etc. Is that correct? What are the things that come first? We went through these yesterday. If you have porosity, again you have hydrogen, so what are the most important sources of it? If you're running a good operation, what are the most important sources of it? If I had to choose the number one, I would say the surface of the wire, and the surface of the plate. Next to that, I'm assuming that you have a pretty good shield. Next to that, I would say the real efficiency of the shield that you have, is that you keep moisture from the air out. Next to that, and again assuming that you have a pretty good operation, you'll get perhaps some through the gas, and some through faulty equipment, some little defect you have in the tube somewhere. And probably the last one that I would put down is that quantity which is inside the base plate and inside the wire. Now, this doesn't say that we can neglect any of them, but if I had a porosity problem and I'm running a pretty good operation, this is the order I would look in. Where is the hydrogen coming from? Now, you have to have the hydrogen in order to get the porosity. All of these other things that we talk about, welding in the 3 o'clock position, overhead, downhand, fast, slow, high arc voltage, or this, that, or something else, just say whether it comes out or whether it freezes in. If it comes out, there's no problem. But in the 3 o'clock position, or perhaps the overhead, it gets trapped in. So, this is a problem.

Mr. Ingram: I like your summary there, Perry. I'd like to make one comment before Bob leaves here. I think you've covered the fundamentals of this problem rather adequately. However, I am reminded of the early work that was done in aluminum structures for ships. That hasn't been too many years ago, back in the late 40's when inert gas welding, you might say, was put on its feet as a real process. We had porosity, plenty of it. We covered these variables that we have been discussing here for the last several days. These were cleaned up to some extent, including additional degassing of the base metals when they were poured; however, one thing holds true of the various structures that were involved at the time, like tripod mass on destroyers, complete shiphulls, not very big ones, 100 foot, 30 foot beams. The way we got around the bulk of this, after cleaning up wire, reducing the water vapors, and gases etc. was merely by technique, and that technique that was used would vary with the amount of wind that happened to be blowing around the shipyard. In other words, we would increase the volume of gas for shielding. We'd give it as much shielding as possible. Now, this may not have been the most economical cure, but it did serve the purpose. I think we've come a long way here. I often wonder how many measurements we make, and particularly here in the space picture, in regard to the turbulence of the air around these welds that may have a decided influence on these shielding gases at the time that the welds are being made. It doesn't take a heck of a lot, and if you're using helium or large percentages of helium, the effectiveness of this turbulent air around you can do an awful lot of damage here. I haven't said anything new, but I like Perry's remarks.

I merely wanted to point out that this thing got a start in aluminum by doing pretty much the very things we're talking about at the moment. But shielding gas, and enough of it, with nozzles that have been designed to give you linear types of flow, rather than turbulence, appears to be one simple route, at least, to a cure.

Chairman, Mr. Brown: Now, gentlemen, we've kicked around quite a bit this morning in the things we've been discussing, and I think that Perry has pretty well summarized it. I think that before we close out, we should take some time to do one thing, and that is to leave some recommendations here with our hosts at NASA as to what can be done to continue this. I don't think anyone disagrees with Harry's idea of getting rid of hydrogen, but it reminds me a little bit of a friend of mine one time who was very discouraged. I said, "What's the matter, Joe?"

And he said, "Hell, I feel like sleeping with Jayne Mansfield again." And I said, "Again?" And he said, "Oh, yes, I've felt like this before." So, its not enough to feel like that. The question is, what are we going to do about it? And I think that in view of this rundown that Perry's given us in his summary, I would like to ask these panel members now to tell us what can we do about this, how can we pin some of these things down and prevent them, and where should we go from here? How should we maintain the type of coordination we've had at this meeting? I'd like to ask the panel and then I'll ask some of you people on the floor. Who would like to start commenting? What can we do about this? Where do we start to put a handle on these factors of control?

Panel, Mr. Vilkas: I guess the immediate suggestion would be to turn to the highest percentage of incidents as recorded by some means. We heard what Martin did in Denver. I think it should be done here. That's where the problem should be attacked first. Not talking about the welding problem as such, but a problem defined by some means. For example, it was mentioned that one of the problems with this porosity was that the equipment is not yet producible, dependable, and so on. It should be simplified, etc. Now, that is fine. That's what people should work on. But at the same time, I think that the facility people, people that are in charge of fabrication, should develop statistical methods to define the causes for these defects in the welds.

Panel, Mr. Davis: We have of course, as Perry pointed out here, two main problems in the cleanliness of the materials--the filler wire and the base material, and of course assuming that you have a good shielding gas. The filler wire comes to us fairly clean, and we package it and store it, keep it properly concealed so that it doesn't get recontaminated; so, this leaves the base material. Of course, we have to work with this up to the point of the welding operation. So at this point, we need to put special emphasis on the cleaning of the base materials in and adjacent to the weld. I think one of the big problems here is in the magnitude and size of our vehicles. It's almost impossible to get this clean in ten minutes and weld ten minutes later. But, I think this is what we should strive for, getting it clean fast and weld as soon as possible after the cleaning operation.

Panel, Mr. Hackman: I think a session such as we're completing here is very good. We do get a lot of interchange, so long as we don't conduct it on the basis of a bidder's conference, where, as competitors, we tend to sit a little bit on our hands and see if someone else will expose the idea that he intends to use in his bid. Otherwise, you tend to get a freeze up. I think one way to keep an interchange of information going, certainly, is a session like this, but I think also I would put the burden of responsibility right here at the Flight Center. Publications such as the one that has just come out here, The Survey of Welding Problems, will help us a lot; also, to regularly receive, let's say, you're own progress reports; also, the reports coming from the people who have sub-contracts. A great deal of what we heard in the last few days has been duplication and it's no one's fault. We find that we are sometimes working on the same problem. And, getting back to a comment I made at the beginning, I don't think our problem is broadly, porosity in aluminum. It's porosity in aluminum in specific weldments, specific joints. And after all, the end object here is not to generate data, or X-ray film, or anything else; it's to build a space vehicle. I think the specific problems on the specific joints, clearly defined to us, are the things we ought to work on.

Panel, Mr. Baysinger: Yes, this idea of a technical interchange is very good. The specific request made, though, at the beginning of this latest discussion, was for ideas for future specific work to be done, and with reference to the specific weld that is causing the difficulty, the 3 o'clock weld. If you analyze that, you have two things as variables--the plate material that can melt into the weld, and the shielding efficiency that was pointed out very clearly. So, if that is the troublesome weld, it is certainly suggested that attention be given to this weld, and to the relationship to the parent metal, establishing a hydrogen level, and taking a good look at this specific weld. It is agreed that the vertical welds are of no particular problem. I think this is true because whatever is in there fuses, has time to rise out of the weld, and does not remain in it. It is only the stuff that is churned up, boiled up in the weld that rises to the top in a 3 o'clock weld, and there it stays. It hits the solid metal and it stays there. The suggestion that the specific problem be worked on is good. I suggest that we work on the 3 o'clock weld, and from a very basic standpoint.

Panel, Mr. Lenamond: I'd like to say just one other thing about this dissemination of information, and in carrying on such meetings as we've had here this year. I think it's a must that we do this. I'm sure that there has been some thought given to setting up a library here at Marshall. I'd like to put this out as a proposal, and it might be in the making; I don't know. But, we're talking about interchange of information here, and if it would be possible to set up a library, in which all of NASA's internal work, and all of the contractors' reports could be filed, and could be made available to future contractors, and any one particular area in which a new contractor is going to start to work, if he could obtain all of the information available, this would certainly tend to cut out duplications, and help these individuals.



Panel, Mr. Schwartzbart: Specifically, along the lines of communication, I suggest that NASA give some specific consideration to how to handle the distribution of reports. Different Government agencies use different practices. I think there should be distribution lists, and I think the philosophy ought to be taken that the distribution lists should be large rather than small, as they are in some Government agencies, and that the work that's going on ought to be widely disseminated. In addition to the library, other means ought to be taken to avoid duplication of effort and keep everyone as well informed as possible.

Panel, Mr. Rieppel: I might say one thing more here. I think something has been quite lacking in this discussion. I mean there's been lack of information. That is, just how much porosity or what defects can we take, and what can't we take. This is certainly one area where we must in the future do a lot more work. I look at it again just from the point of porosity, and I have no hopes that we're ever going to get rid of all of it consistently. But, we need to know more about how much can we take, how far do we have to squeeze this thing to have it good enough. And I go back to the old saying that the best engineering job in the world is the one that's just good enough. But, it's awful hard to just do one that's just good enough. We need to know more about the side of this thing of what can we take and what can't we take.

Mr. Cline: I discovered in the last few days that when we were the prime contractor for the Reactor in Flight Program we did some very interesting work on shrinkage and distortion. We developed some empirical shrinkage formulas, mathematical equations, quite simple, based upon single pass welds in aluminum plate. One plate thickness alone, we found that this was fairly reliable. Now, getting back to a statement that someone made on the panel a few minutes ago, those reports have been in the Marshall complex for five to six months. A great many of the people that should have seen them at MSFC have not seen them.

Chairman, Mr. Brown: Well, gentlemen, in preparing to turn this meeting over to Mr. Parks again, I'd like to take the liberty, or the prerogative to make summary comments on what I have reduced from what the experts have said here. First of all, there should be a great deal of weight given to one thing. We should have some idea from the quality control point of view as to how serious the defects are, how many of them can we stand, how much of them can we stand, and exactly how are they occurring? I was particularly impressed by the fellow who turned up with 85 percent human factors that he could prevent. There are a certain number of weld defects that got through which he did not prevent, but at least he eliminated the things that he could control before he cried out that the metal was poor, the vendors were not responsible, that the equipment was no good. I think that this is the important thing to clean our own shops first. I think that it's important that we have these standards that Perry spoke about, to know what is required of us. I think in return that every single vendor, whether it be material, or whether it be equipment, has the right to ask every one of us that has made any comments, "All right, what do you want? Why don't you tell us? Don't talk in generalities. You want better equipment; what is it

you want?" Mr. Manary, this morning, spoke of a definite range of 15 that he wanted a control on. He thought this wasn't adequate. Now, if he can set this figure at some lower value, the equipment vendor can say --- we can't do this. That's one thing. But we should be specific. What do we want in metals? Base metals and wire? What do we want from the vendor? How much do we really need to do the job, and how much is it going to help us? What good is it going to do us if he has the wire spotlessly clean, and he ships it and it's not in that shape by the time we get ready to weld it? I think these are questions all of which should be answered too. And, to review, I think the important points that Perry summarized were: first of all, we know we must eliminate hydrogen. Second, we have learned that the metal surfaces are important, both the filler wire and the base metal. They must be clean. The efficiency of the shield must be examined to exclude the ambient conditions where you can get into trouble. Faulty equipment is certainly going to happen once in a while. The internal property of the metal, filler wire, and the metal itself are certainly open to question.

Now, as Perry said, it's probably unlikely that we shall ever eliminate all of these things at the same time and have 100 percent. But somewhere along the line, as someone said this morning, we have to set up a certain standard to which we are going to work for any process. At least set a consistent working range. If we're limited by materials, at least set a consistent standard to use. If we're going to have a shielding gas, at least be sure that what goes in is the best that we can give the men working on the job. If we start to eliminate the variables that we can control, then perhaps we'll have a right to come back to people like NASA and say, "We've done what we can to control, but you're asking too much of what we can offer." Now, has this been a fair statement, do you think, gentlemen? Before I let the panel go, have they done the job you wanted them to do, or is there something more you'd like to ask them? In that case, I'll turn it back to you with many thanks for all your courtesies.

Mr. Orr: This will be my last time up here. I'd like to thank all the speakers, the panel members, co-chairman, and all the attendees for a wonderful gratifying meeting that we've had. We have really enjoyed it, and we hope you've enjoyed being with us. Hope you all got something out of it. Bob Hoppes is going to come up and give us a little message. I want to thank Bob Hoppes, in front of all of you, for the fine job that he did in organizing this thing. I think he's really to be commended on that.

Bob Hoppes: The fact is, I'm sick of standing in the rear. This will take one and seven-tenths minutes, approximately. We are happy indeed that you have come to this symposium, and I am particularly happy. As late as Monday, I often imagined Mr. Kuers and myself---alone---in this huge auditorium. Even the presence of Mr. Parks and Mr. Orr would hardly have added to my comfort. I would not have stayed any longer than necessary. But you did come.

I wish to thank in particular the technical co-chairman and the lecturers. It was an excellent group of papers. I also observed with interest the principle of evolution at work. Over the past 216,000 seconds,

I have seen the transformation of a group of engineers from artists to scientists. I am pleased. I hope you do well in your new role. Well, those were not closing remarks.

I wish to restate the two major themes of this Symposium, and I hope, of the years ahead of us. First, the coordinating, and bringing together, and integrating of the development efforts of NASA and industry. This means the exchange of information, mutual planning and development, resulting in, I hope, another Symposium of greater magnitude and consequence. The second major theme has been to elevate the welding complex to a more scientific level, to search for basic causes and effects, and to apply this knowledge to our present and future problems. In such a manner, we can attain improved quality in welds and, thus, higher reliability in welded structures. Those were closing remarks.

Now, as my San Antonio friend, Norm Lenamond would say, "Hasta la vista, y que le vaya bien." Adios. The conference is adjourned.